NASCTN Project: “LTE Impacts on GPS” Final Briefing

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National Advanced Spectrum and Communications Test Network

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Outline

- NASCTN – who we are
- Statement of work
- Overview of testing methodology
- Key aspects of the test methodology
- Test setup
- Data parsing and analysis
- Results

NASCTN

National Advanced Spectrum and Communications Test Network

A neutral forum for addressing spectrum-sharing challenges in an effort to accelerate the deployment of wireless technologies among commercial and federal users. NASCTN was created in 2015.

National Institute of Standards and Technology
U.S. Department of Commerce

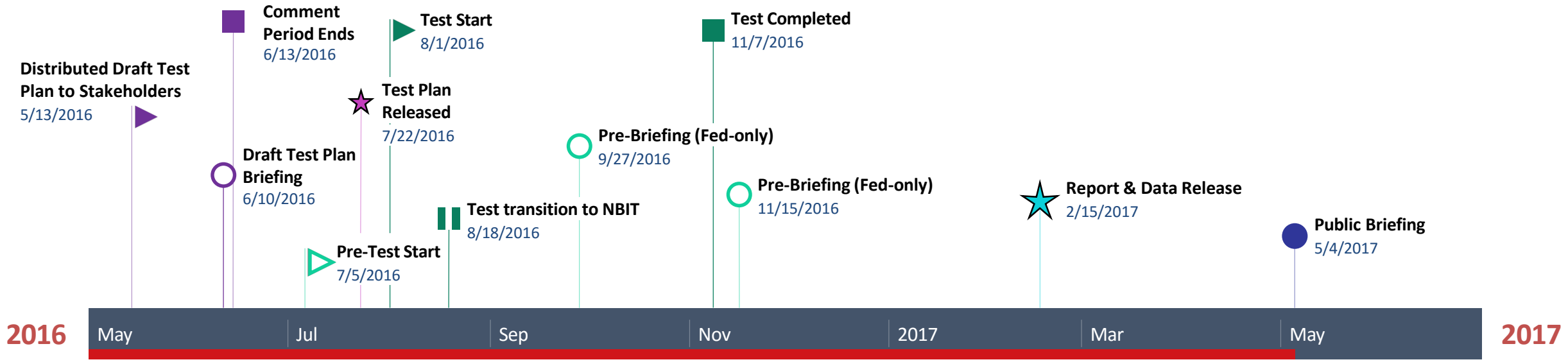
NASCTN - Mission

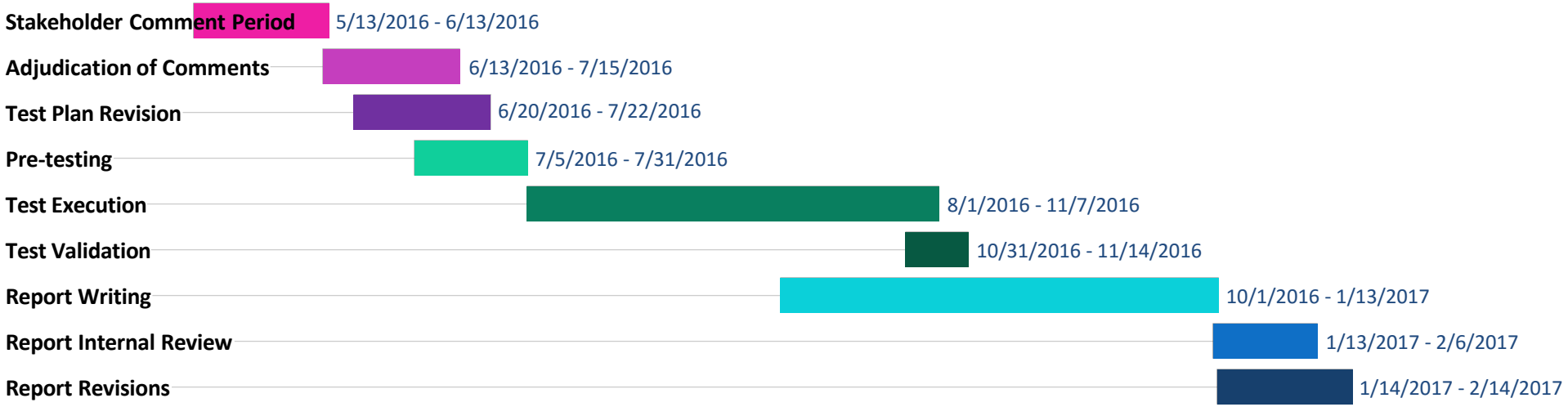
Provide robust test processes and validate measurement data necessary to develop, evaluate and deploy spectrum sharing technologies that can increase access to the spectrum by both federal agencies and non-federal spectrum users.

1. What we do
   a. Develop test plans with independent technical experts
   b. Identify and facilitate access to appropriate test facilities
   c. Execute, and validate rigorous test methodologies and results
   d. Inform stakeholders and public
   e. Protect proprietary, classified and sensitive information
2. What we don't do
   a. Policy recommendations

“LTE Impacts on GPS” Timeline

LTE - Long Term Evolution
GPS - Global Positioning System
NBIT – National Broadband Interoperability Test Bed





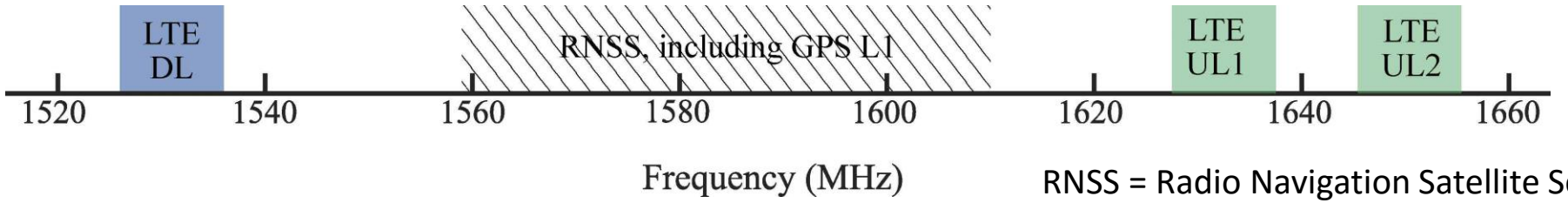
Statement of Work

Objective: Develop a rigorous, focused testing methodology to measure the impact of LTE signals on a subset of GPS-based devices.

1. Foundations in scientific and engineering best practices
   a. Reproducible
   b. Calibrated measurements
   c. Statistical analysis of the data
2. Portable and extendable to
   a. Great variety of GPS device classes
   b. Diverse set of end-use cases
   c. LTE – architectures
3. Focuses on changes in device reported Key-Performance-Indicators (KPI)
4. Presents data in a manner that supports discussion amongst stakeholders and is transparent to the public

Scope

Fig 1.1 pg 2



RNSS = Radio Navigation Satellite Services

- Ligado Networks proposed LTE bands
  - Downlink (DL): 1526 MHz – 1536 MHz
  - Uplink 1 (UL1): 1627.5 MHz – 1637.5 MHz
  - Uplink 2 (UL2): 1646.5 MHz – 1656.5 MHz
  - Simultaneous Downlink + Uplink 1
- Terrestrial GPS – 20 receiver configurations
  - General Location and Navigation (GLN)
  - High Precision Positioning – Single Point Positioning mode (HPP)
  - High Precision Positioning – Real Time Kinematic mode (RTK)
  - GPS Disciplined Oscillators (GPSDO)
- LTE in-band and out-of-band emissions, as filed to the Federal Communications Commission (FCC):

  "Comment Sought on Ligado's Modification Applications (Public Notice DA 16-442)," Federal Communications Commission, Washington, D.C., Apr. 2016, pp. 10–12 (cit. on pp. 25, 27, 61).

Test Summary Statistics

3 Month measurement campaign

- 1476 Test hours
- 38222 Raw data files
- 19220 Parsed data files

Deliverable: 3859 data files (780 MB)

Encompassed:

- 968 LTE exposure tests
- 83 Timing tests
- 5155 Time-To-First-Fix tests
- 891 Time-To-First-Reacquisition tests

Overview of test methodology

- **Device-Under-Test (DUT):**
  - **Reflect recommendations from a variety of stakeholders**
  - Access to measurands is a key consideration in device selection
  - 5 General Location and Navigation (GLN); 4 High Precision Positioning (HPP) with 2 in Real Time Kinematic (RTK) mode; 3 GPS Disciplined Oscillator (GPSDO); 2 Development Boards (DEV) with 1 in GPSDO mode
- **Test Environments:**
  - **Representative LTE waveforms and out-of-band (OOB) emission masks stepped through a range of power levels**
  - Calibrated, semi-anechoic and anechoic chambers
  - Simulated satellite constellation, nominal and limited conditions
- **Test Conditions:**
  - Stepped LTE Power level sweeps, Time-to-First-Fix, Time-to-First-Reacquisition, Timing tests
  - DL, UL1, UL2, DL + UL1
- **Measurands:** (Quantities intended to be measured.)
  - **Analyzed: C/N_0, position error, timing deviation**
  - Provided: pseudorange information, and carrier phase information
- **Output:**
  - **Present data in manner that supports discussion amongst stakeholders**
  - Data sets of collected measurands versus LTE signal power levels
  - Statistical analysis: compare distributions of measurands with and without LTE

Measurement Environments

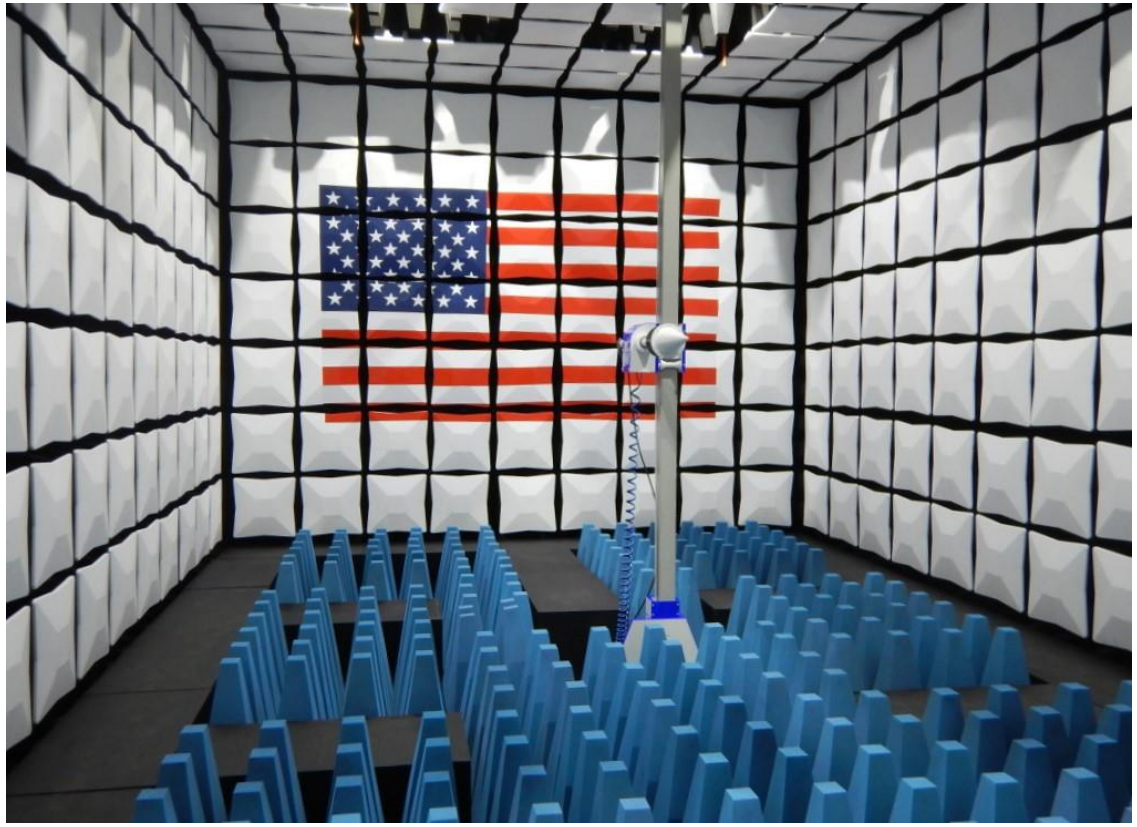


Fig 3.6 b pg 43

Campaign made use:

10 m semi-anechoic chamber

(NTS in Longmont, CO)

5 m anechoic chamber

(NBIT at NIST – Boulder, CO)

Chambers are well characterized for:

- Noise isolation
- Multipath effects
- Environmental stability
- Minimize interference from instrumentation

GPS Simulator

GPS Use Case: physically realizable, controlled, and metrologically quantizable.

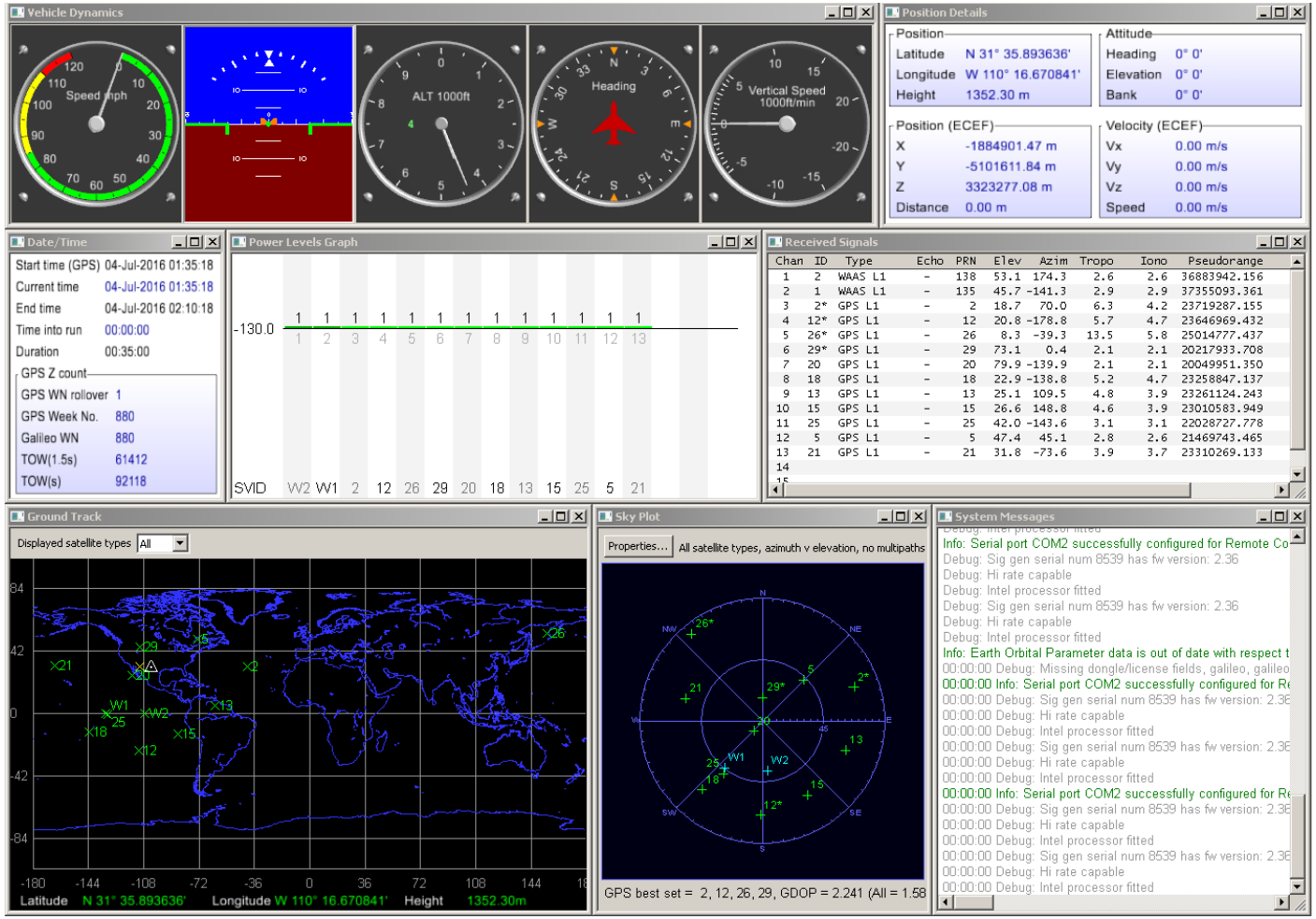


Fig C.1 pg 277

GPS simulator best addresses rigorous testing requirements

Precise control over:

- GPS signals
- Augmentation signals
- Signal power
- Atmospheric effects

Traceable satellite constellation

- Position
- Horizon transitions

Reference truth for KPI

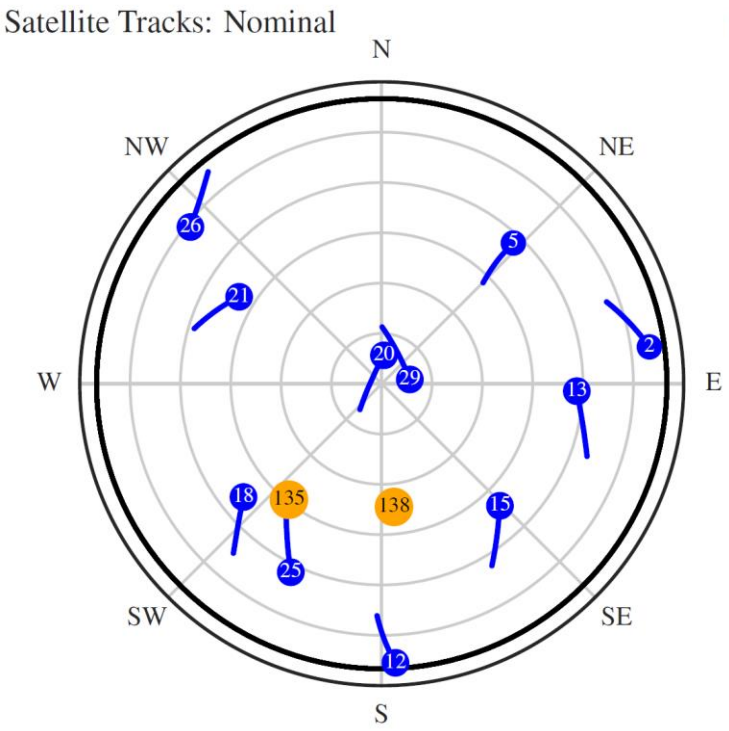
Automation & Time syncing

Satellite Constellation – Stepped Power Levels

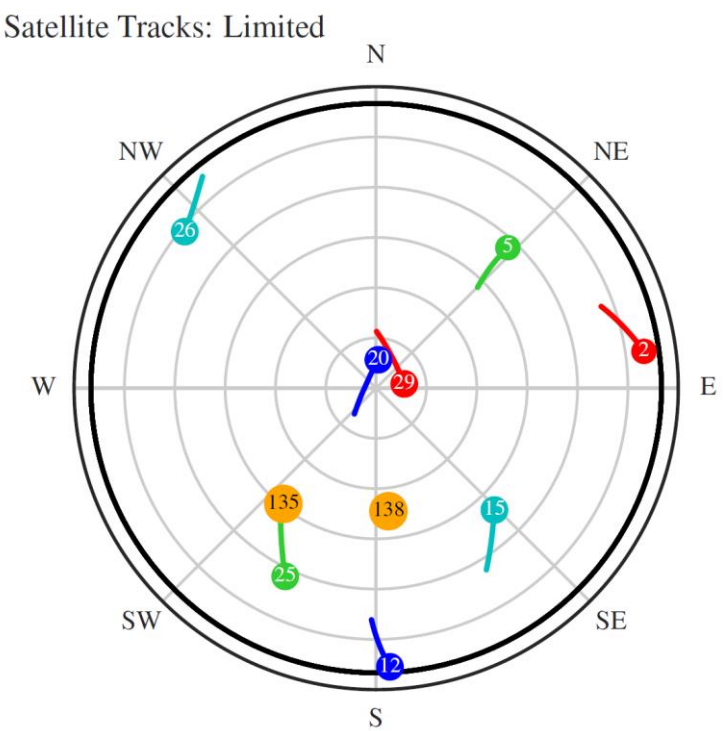
Fig 2.2 a, b pg 21

- Nominal and Limited exposure settings
- Constellation features
  - GPS L1
  - WAAS (Wide Area Augmentation System - PRN 135 and PRN 138)
  - Tropospheric and Ionospheric effects
  - 5 deg. elevation mask
  - **No satellite transition over horizon throughout run time**
- Satellite orbits modified to 24 hour period
  - Allows **identical constellation** for each power level step

- Two Satellite Exposure Conditions:



Run Time: 35 min



Run Time: 35 min

WAAS
5° horizon cutoff
-128.5 dBm ± 2.7 dB
-133.5 dBm ± 2.7 dB
-138.5 dBm ± 2.7 dB
-143.5 dBm ± 2.7 dB

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LTE Waveforms

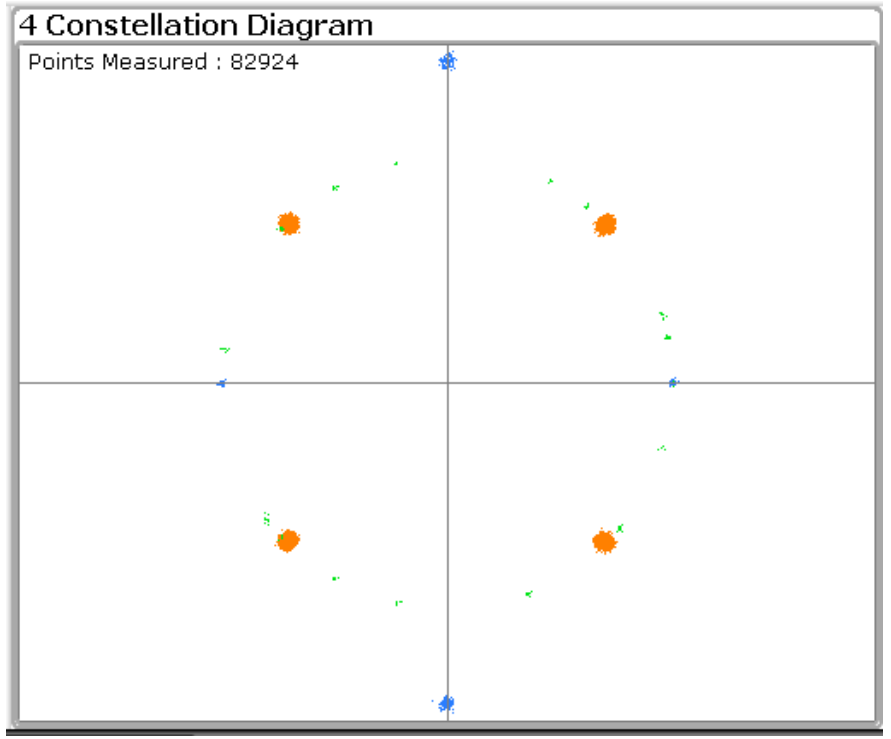
Actual LTE modulation waveforms, verified by error vector magnitude

- Downlink in-band waveform is emulated LTE with 10 MHz bandwidth and 100% loading.
- Uplink in-band LTE waveforms with 10 MHz band allocation and 70% loading, signal occupies the lower 7 MHz of the band.

Out of Band Emissions Masks

- Shaped additive white Gaussian noise
- Defined by FCC filings

From Fig D.14 pg 322



Proposed frequency bands and masks

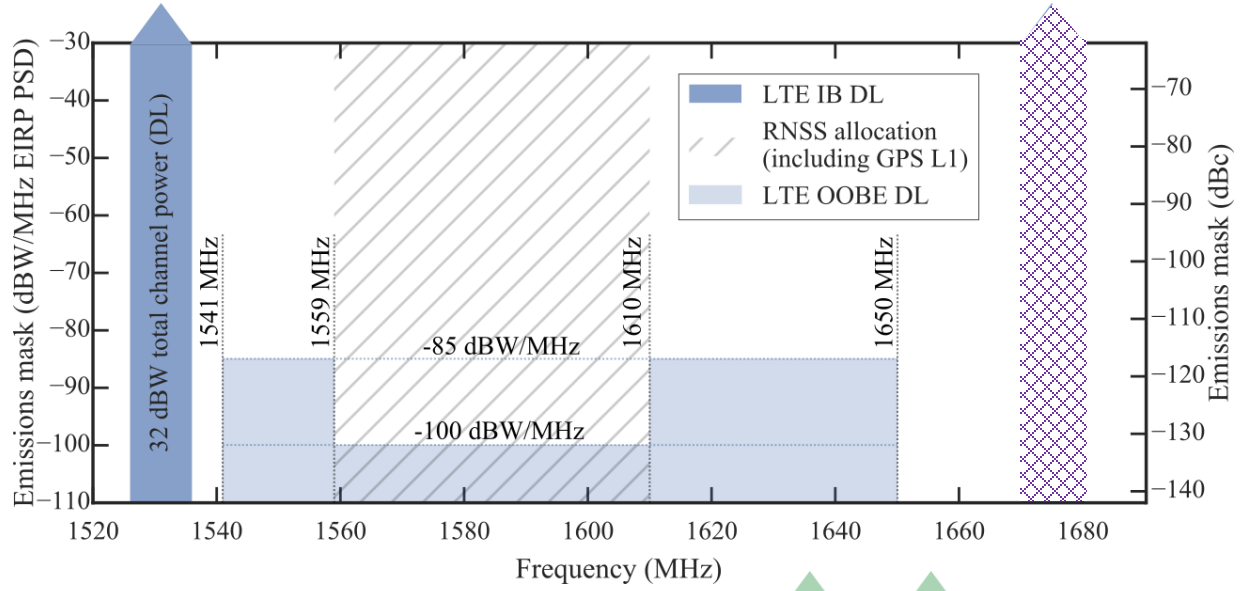
- RNSS 1559 MHz – 1610 MHz
  - Includes GPS L1
- Proposed LTE bands considered:
  - Downlink: 1526 MHz – 1536 MHz
  - Uplink 1: 1627.5 MHz – 1637.5 MHz
  - Uplink 2: 1646.5 MHz – 1656.5 MHz

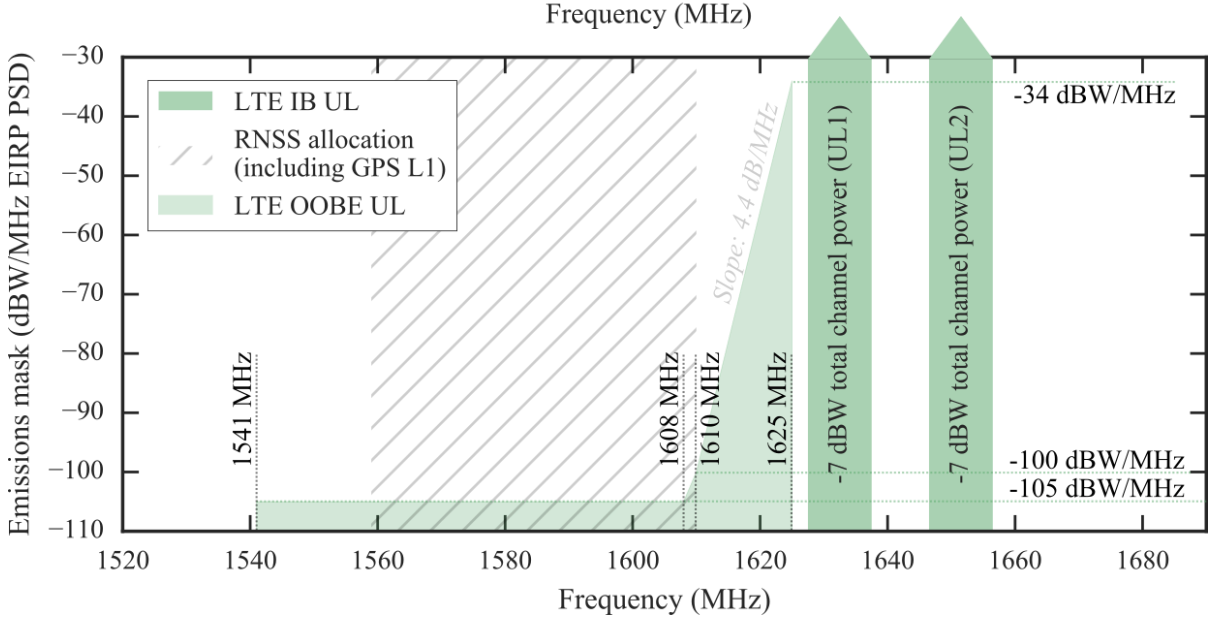
Not part of this test:

Downlink: 1670 MHz – 1680 MHz

- Mask Emulation developed from:
  - In-Band (IB)
    - Well filtered LTE emulation
  - Out-Of-Band emissions (OOB)
    - Shaped Gaussian white noise

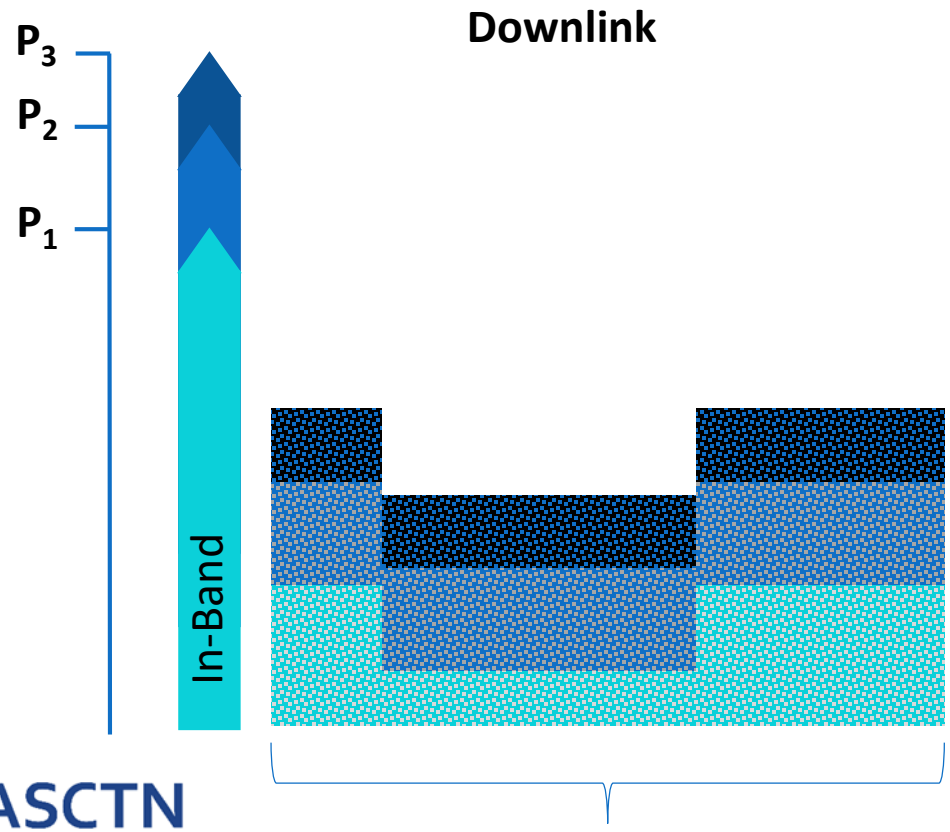
Fig 2.4 pg 27

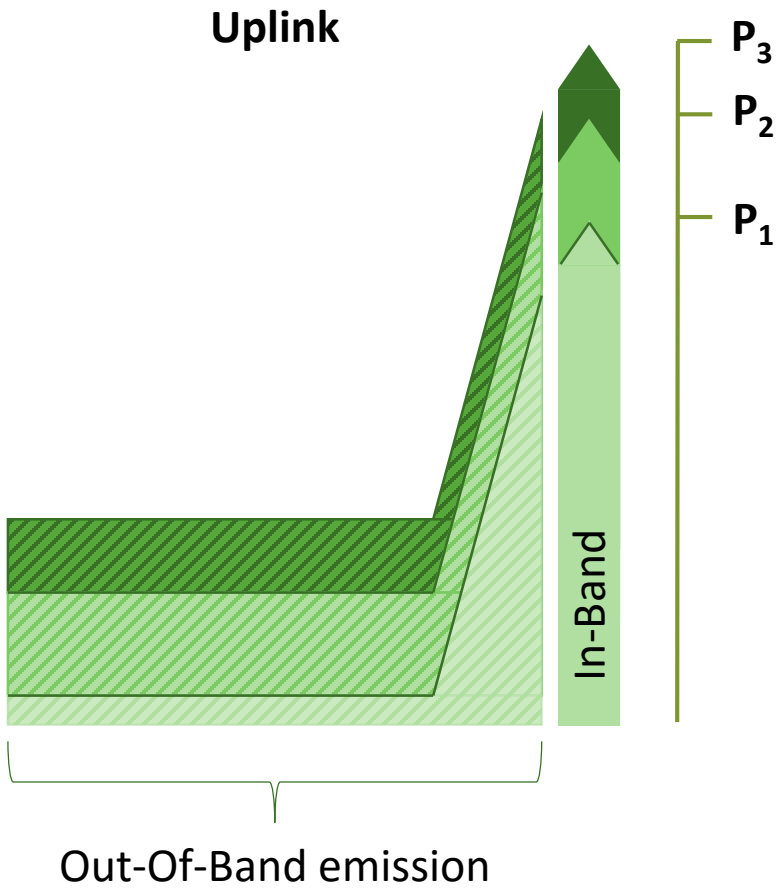




LTE Power Steps – IB & OOB Mask

In-Band and out-of-band emissions mask are stepped in-sync throughout all of the measurements. Simultaneous output of downlink and uplink signals is possible.





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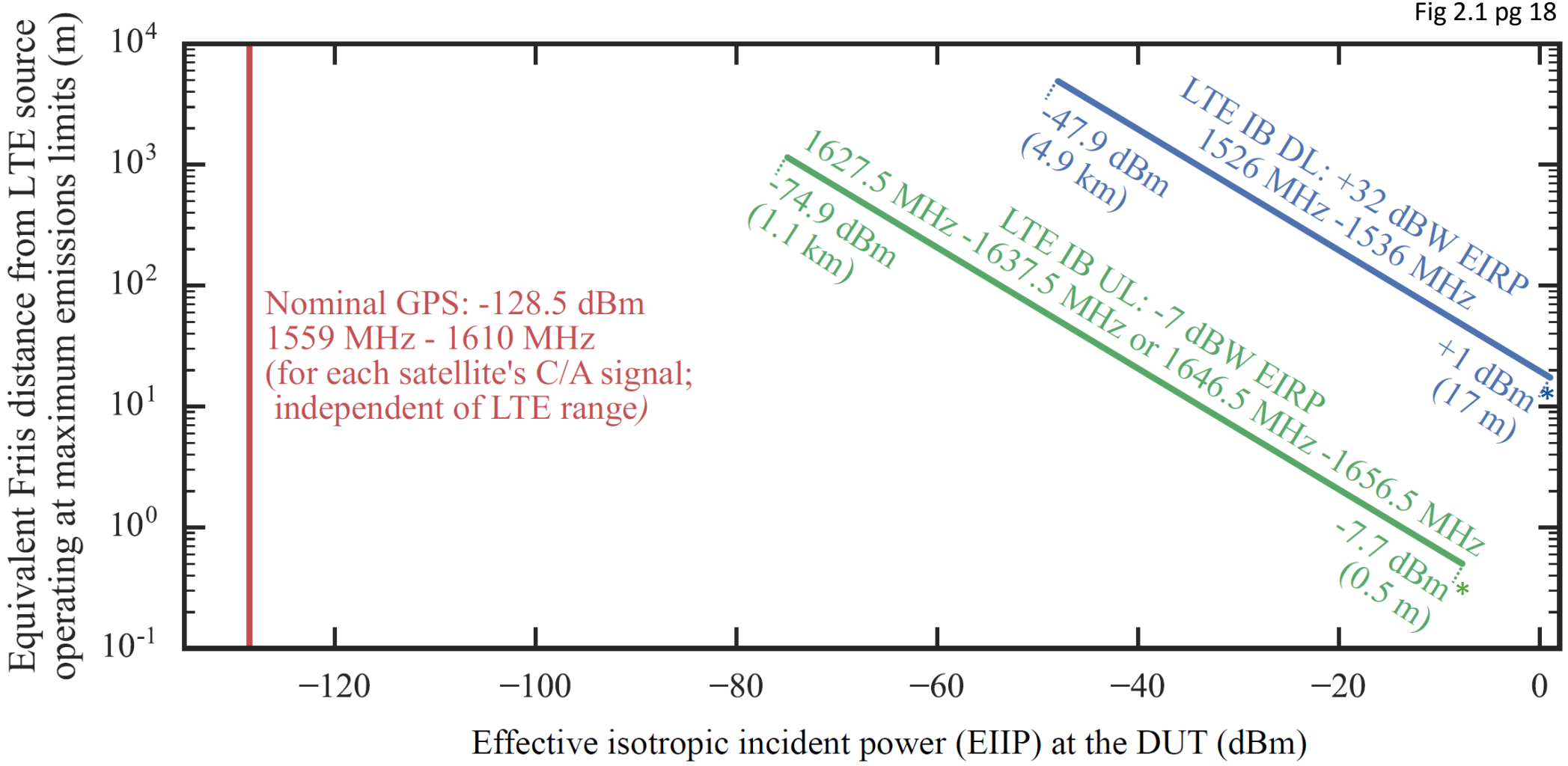
Tested range of power levels

Fig 2.1 pg 18



*Higher power levels as noted in Table 3.6 were possible, but not necessarily tested

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LTE and GPS Signaling Chain

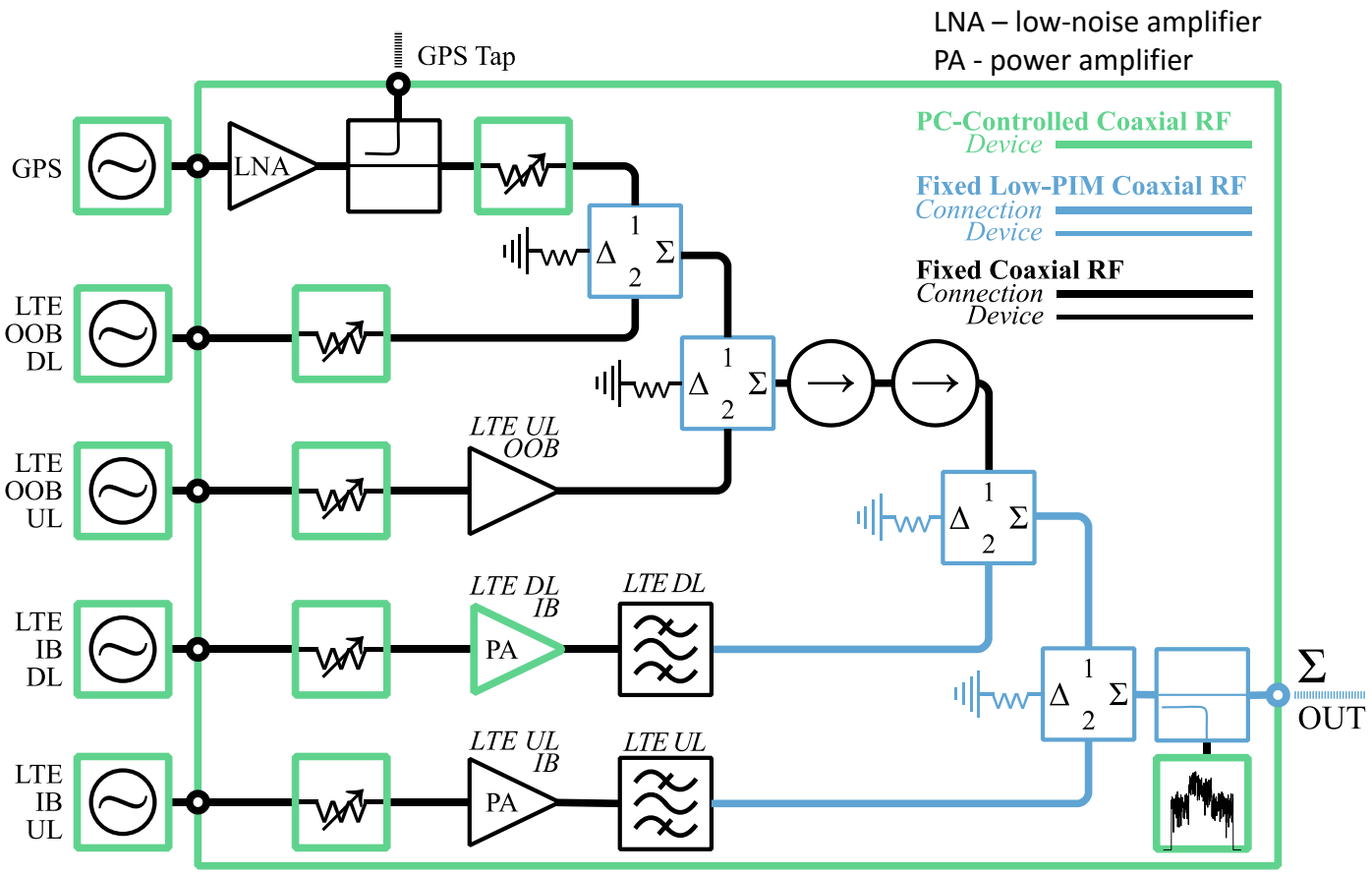

Fig 3.9 a pg 47

Design Priorities

- Operate within safe power handling limits of available parts.
- Isolate amplifiers and signal generators from signals that originate in other signal chains.
- Minimize passive intermodulation along signal paths that carry high-power LTE.
- Maximize test system power output.
- Facilitate automation.

Control the Effective Incident Isotropic Power (EIIP) at the DUT for both the LTE and GPS signals.

LTE Signaling Chain - Test Setup

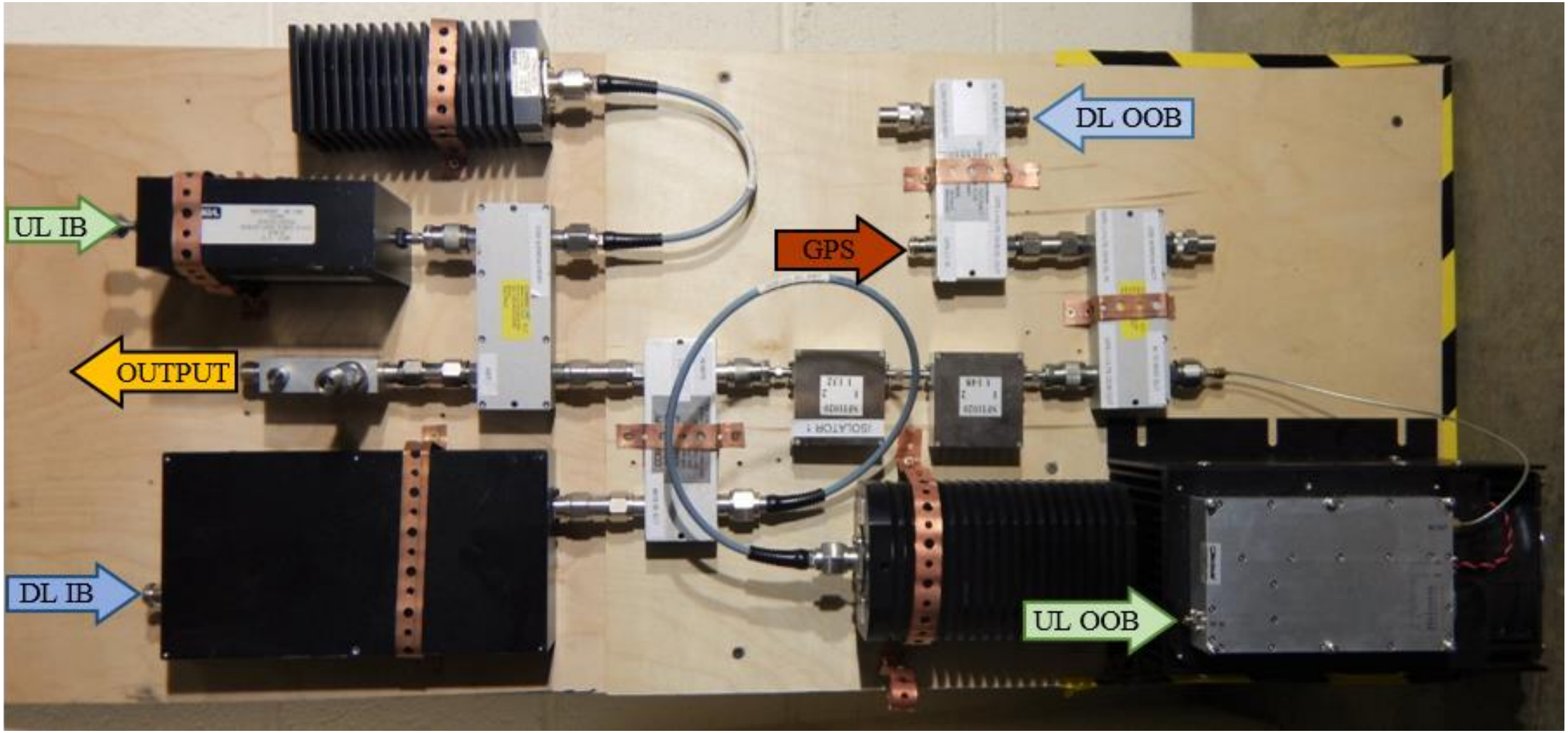

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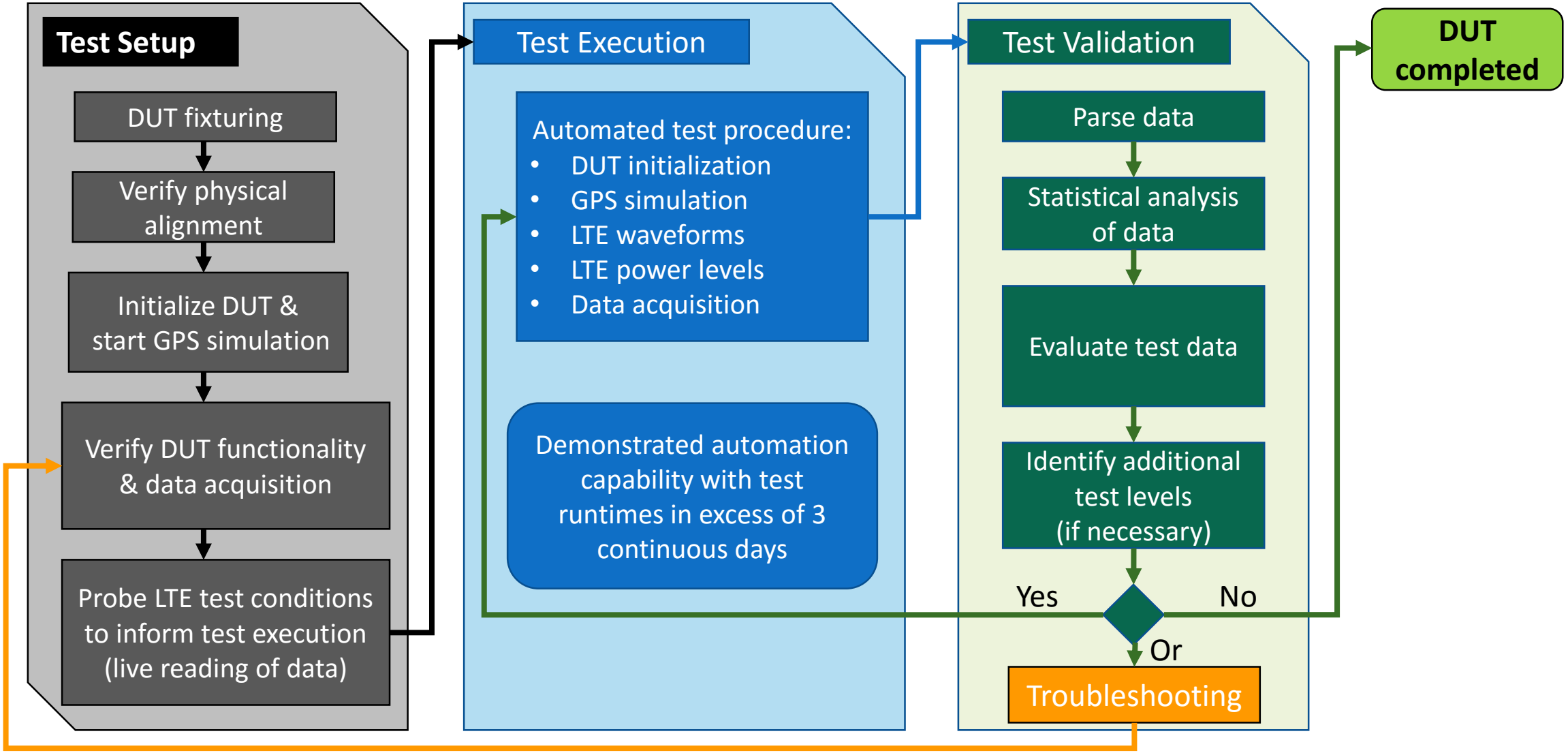
Fig 3.9 b pg 47

Test configurations

- Stepped LTE Power level sweeps
  - General Navigation and Location
  - High Precision Positioning
  - Real-Time Kinematic
- Time-to-first-reacquisition tests
  - General Navigation and Location
- Time-to-first-fix
  - High Precision Positioning
  - Real-Time Kinematic
- Timing Tests
  - GPS-Disciplined Oscillators

Typical Test Execution



Test Scenarios

Class	Device	Antenna	Phase	Test Type	Satellite Exposure	LTE Waveform			
						DL	UL1	UL2	DL+UL1
GLN	DUT 1	N/A	Phase 1	LTE Power	Nominal				
			Phase 2	TTFR	Nominal				
			Phase 3	LTE Power	Limited				
GLN	DUT 2	N/A	Phase 1	LTE Power	Nominal				
			Phase 2	TTFR	Nominal				
			Phase 3	LTE Power	Limited				
GLN	DUT 3	N/A	Phase 1	LTE Power	Nominal				
			Phase 2	TTFR	Nominal				
			Phase 3	LTE Power	Limited				
GLN	DUT 4	N/A	Phase 1	LTE Power	Nominal				
			Phase 2	TTFR	Nominal				
			Phase 3	LTE Power	Limited				
GLN	DUT 5	N/A	Phase 1	LTE Power	Nominal				
			Phase 2	TTFR	Nominal				
			Phase 3	LTE Power	Limited				
GLN	DUT 6	N/A	Phase 1	LTE Power	Nominal				
			Phase 2	TTFR	Nominal				
			Phase 3	LTE Power	Limited				

Class	Device	Antenna	Phase	Test Type	Satellite Exposure	LTE Waveform			
						DL	UL1	UL2	DL+UL1
GPSDO	DUT 13		Phase 1	Timing	Nominal				
GPSDO	DUT 14		Phase 1	Timing	Nominal				
GPSDO	DUT 15		Phase 1	Timing	Nominal				

Color Code
Test Completed & Verified
Deferred\Retired
Not Part of Test

Class	Device	Antenna	Phase	Test Type	Satellite Exposure	LTE Waveform			
						DL	UL1	UL2	DL+UL1
HPP	DUT 7		Phase 1	LTE Power	Nominal				
			Phase 2	TTFF	Nominal				
			Phase 3	LTE Power	Limited				
HPP	DUT 8		Phase 1	LTE Power	Nominal				
			Phase 2	TTFF	Nominal				
			Phase 3	LTE Power	Limited				
HPP	DUT 9	C	Phase 1	LTE Power	Nominal				
			Phase 2	TTFF	Nominal				
			Phase 3	LTE Power	Limited				
HPP	DUT 9	D	Phase 1	LTE Power	Nominal				
			Phase 2	TTFF	Nominal				
			Phase 3	LTE Power	Limited				
HPP	DUT 10		Phase 1	LTE Power	Nominal				
			Phase 2	TTFF	Nominal				
			Phase 3	LTE Power	Limited				
RTK	DUT 11	A	Phase 1	LTE Power	Nominal				
			Phase 2	TTFF	Nominal				
			Phase 3	LTE Power	Limited				
RTK	DUT 11	B	Phase 1	LTE Power	Nominal				
			Phase 2	TTFF	Nominal				
			Phase 3	LTE Power	Limited				
RTK	DUT 12	C	Phase 1	LTE Power	Nominal w/ L2				
			Phase 2	TTFF	Nominal w/ L2				
			Phase 3	LTE Power	Limited w/ L2				
RTK	DUT 12	D	Phase 1	LTE Power	Nominal w/ L2				
			Phase 2	TTFF	Nominal w/ L2				
			Phase 3	LTE Power	Limited w/ L2				

DUT 4 was not sufficiently stable to accommodate test times greater than 3 hours.
DUT 5 did not provide sufficient measurands to present a complete dataset for the purpose of this study
DUT 6 data reporting did not include sufficient number of key measurands of interest to this study, and its control capability presented challenges for third-party testbed automation

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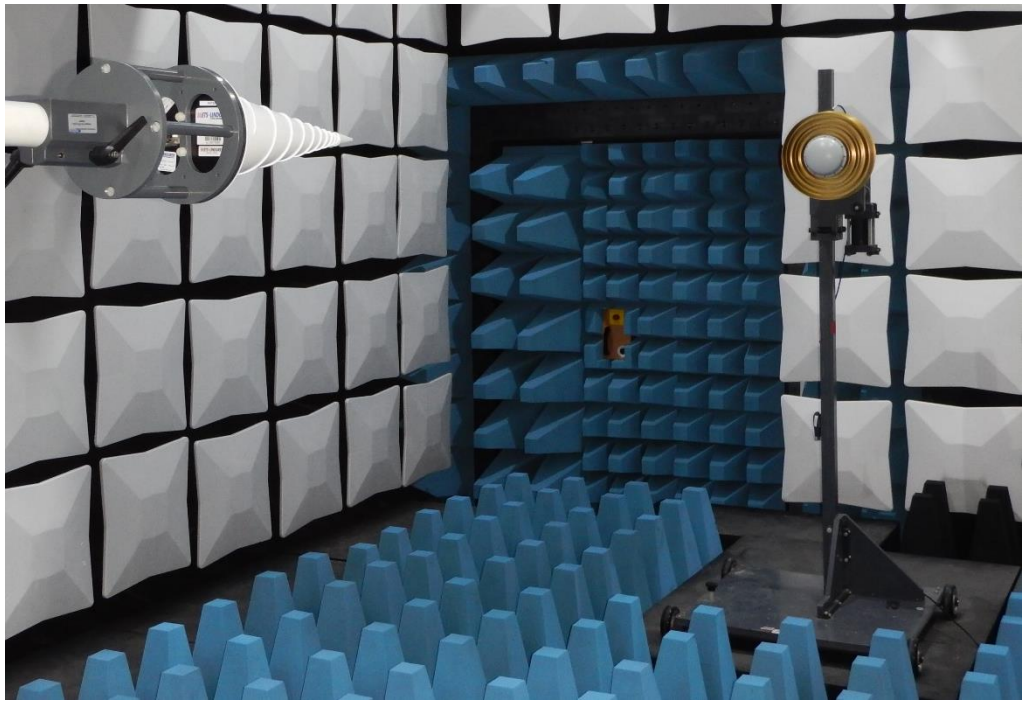
Key Performance Indicators

All available measurands were collected. The following are provided along with the final report:



- Fix quality
- Position
- C/N_0 per satellite
- # of satellites in view
- 1 pulse per second
- Pseudorange information
- Carrier phase information
- Time

Automation

Robust, repeated automated measurements.

- **Portability and expandability of tests**
  - Able to complete complex test-matrix
- **High degree of repeatability of testing conditions**
  - Re-testing of power levels or augmenting test sweeps
  - Repeated measurements agreed
    - Test facilities, testbed setups, & dates
- **Consecutive running of test phases**
  - Substantial improvement in test efficiency (observed ~ 80%)
  - DUT measurements as long as 3 days were achieved
  - Minimal human intervention
- **Rigorous uncertainty analysis**
- **Measurement data traceable to testbed states**
  - No need to rely on DUT provided measurands to time-sync data

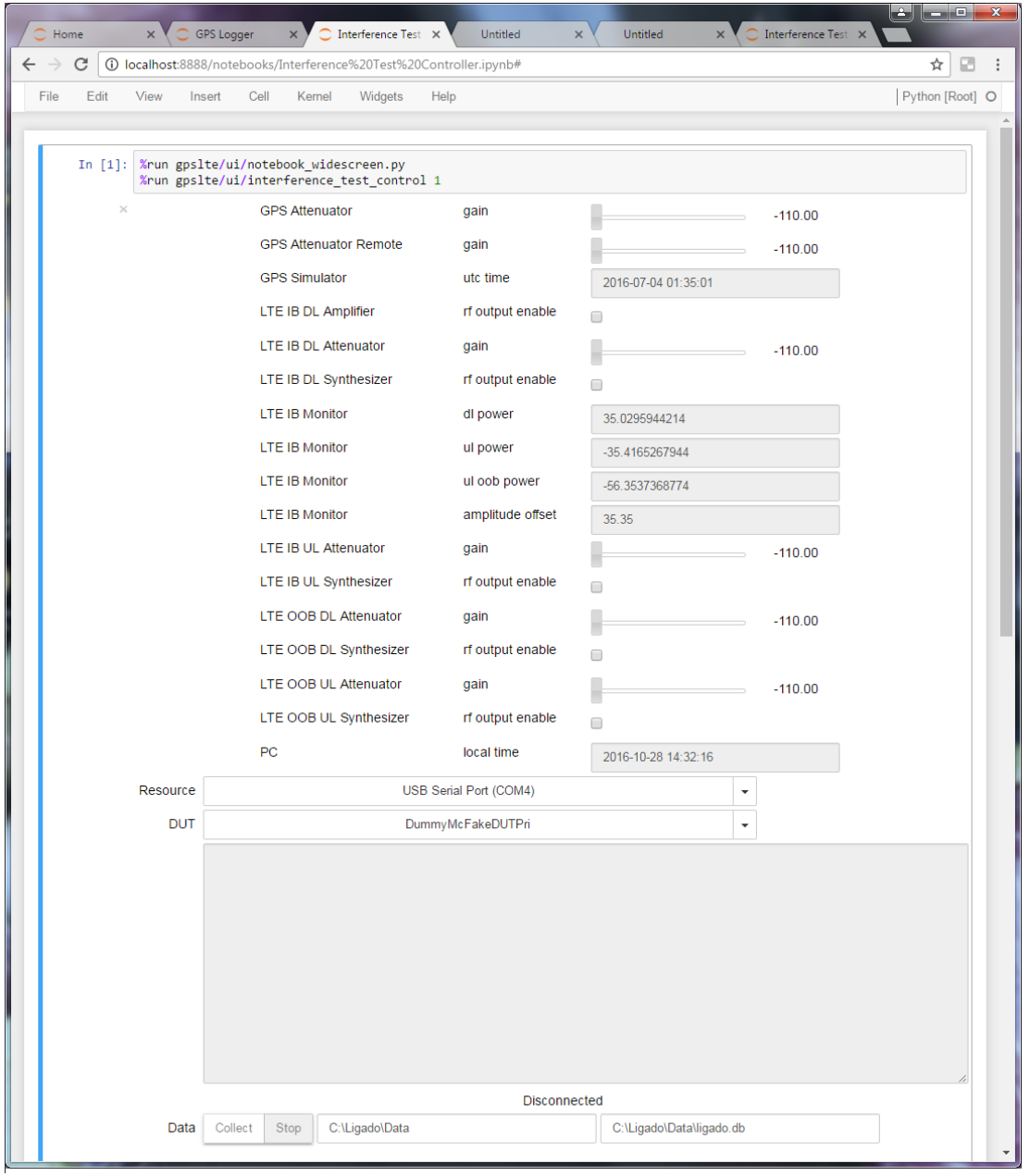


Fig 4.5 pg 68

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Testbed Automation & DAQ

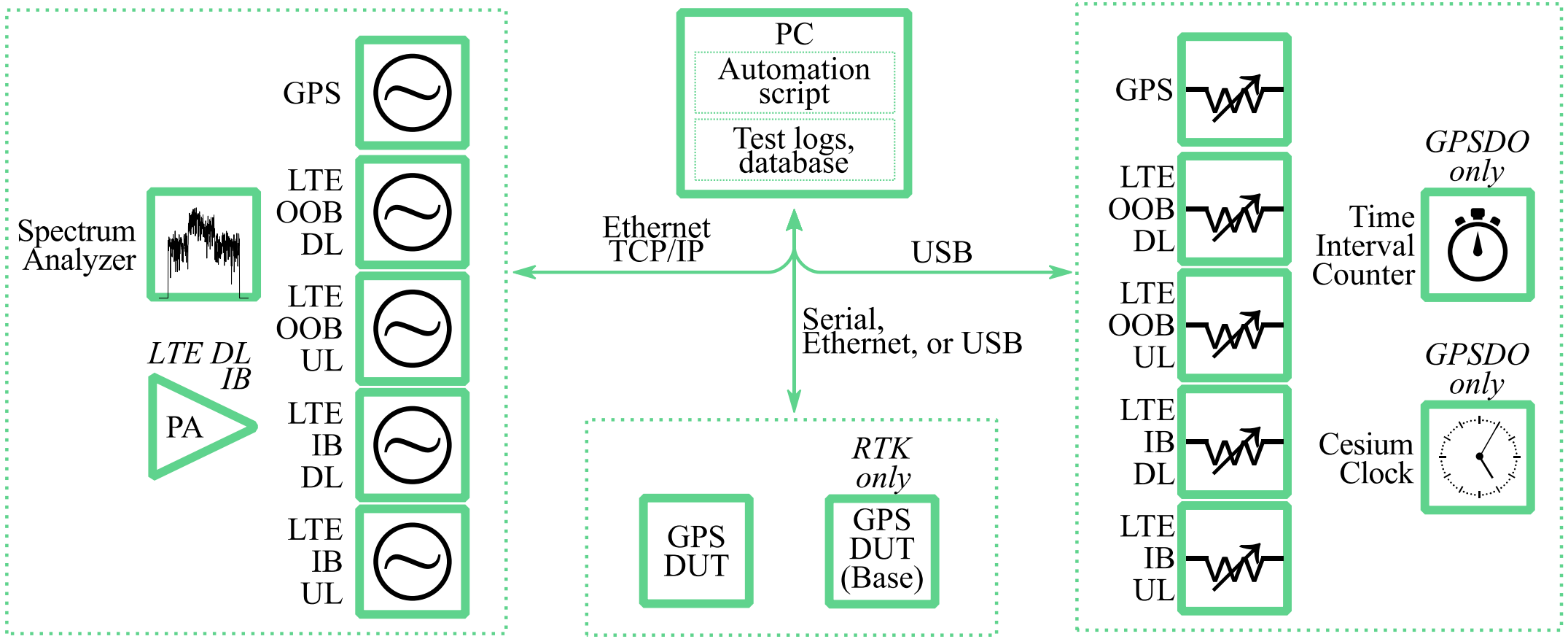


Fig 4.1 pg 64

USB - universal serial bus TCP - transmission control protocol
PC - personal computer IP - internet protocol

Test Setup

- Testing of a single device at a time
- Each DUT is fixed in the same position with respect to the source
- Devices with integrated antennas are placed into the chamber
- Devices with external antennas, only the antenna is in the chamber
- Auxiliary power supply, data cables, etc. were shielded or placed outside of the chamber

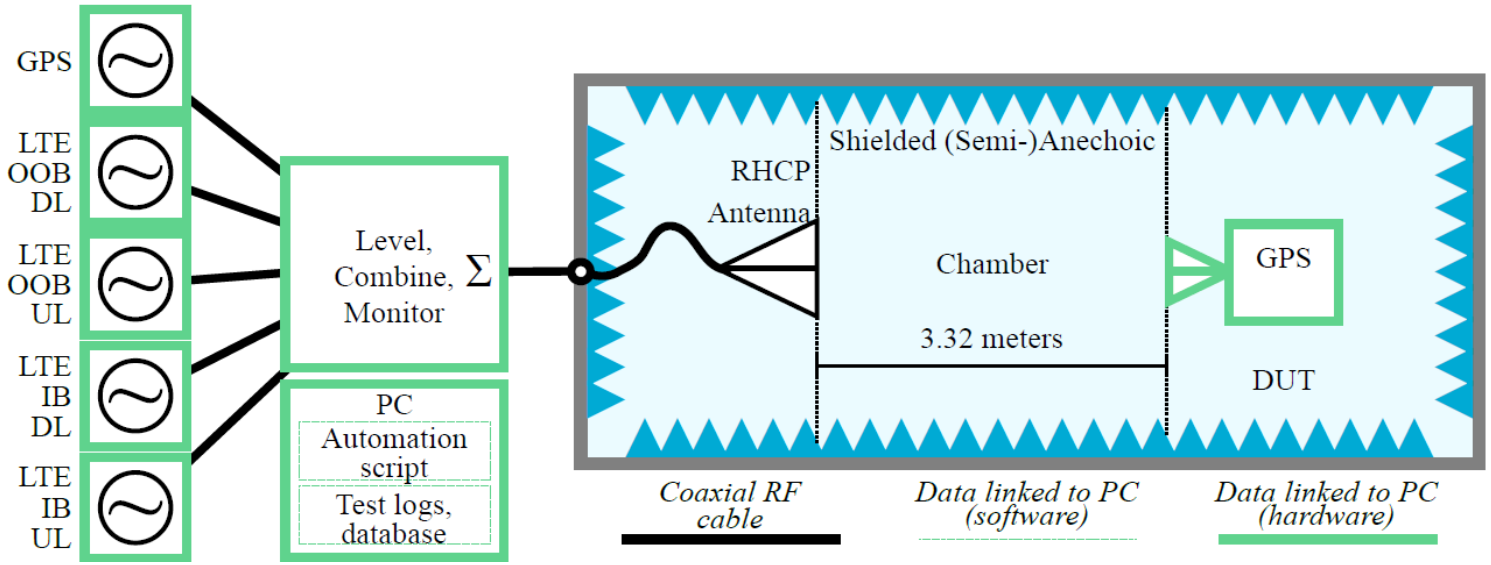
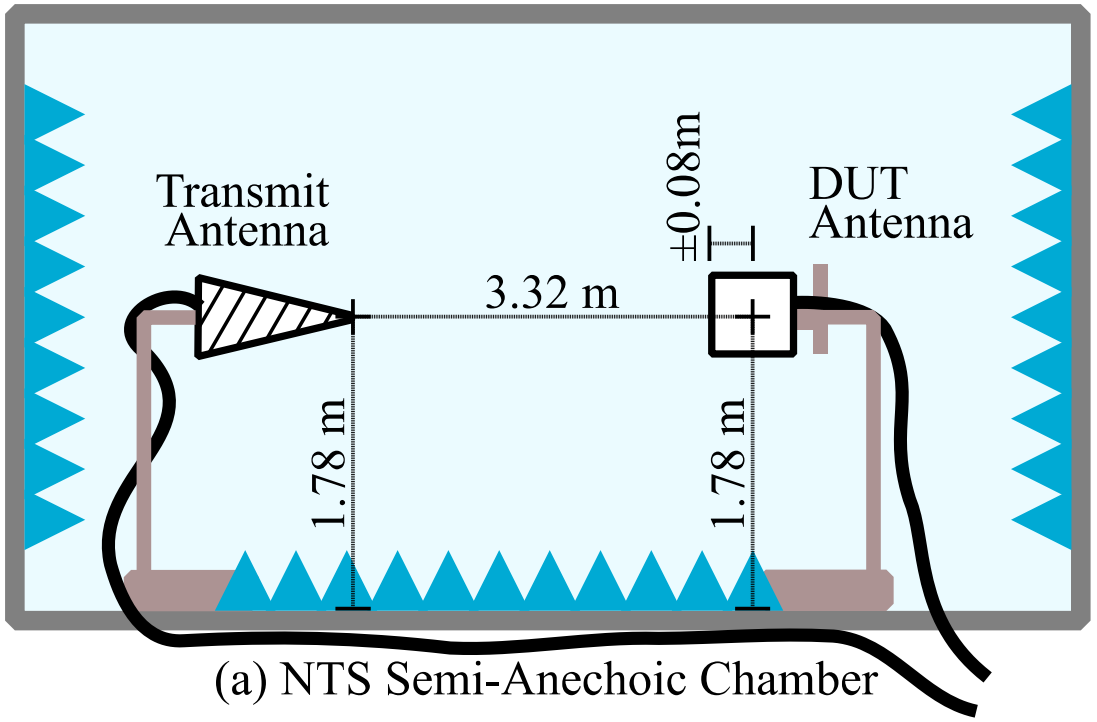


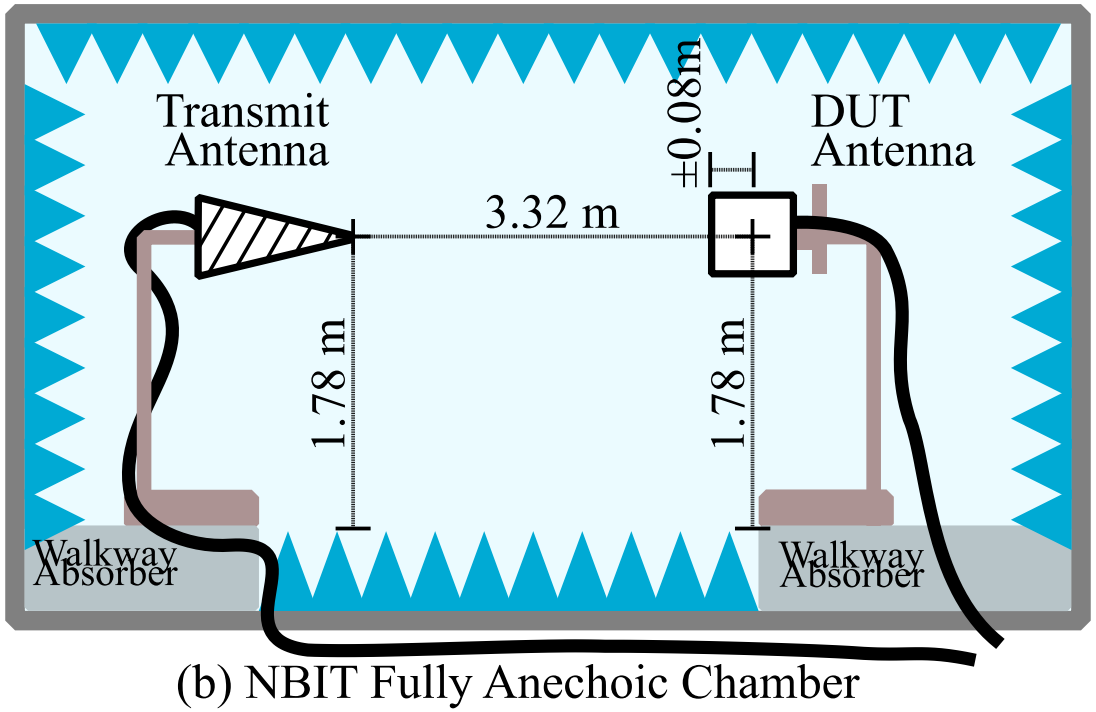
Fig 3.1 pg 39

Device under test placement

Fig 3.7 pg 44



(a) NTS Semi-Anechoic Chamber



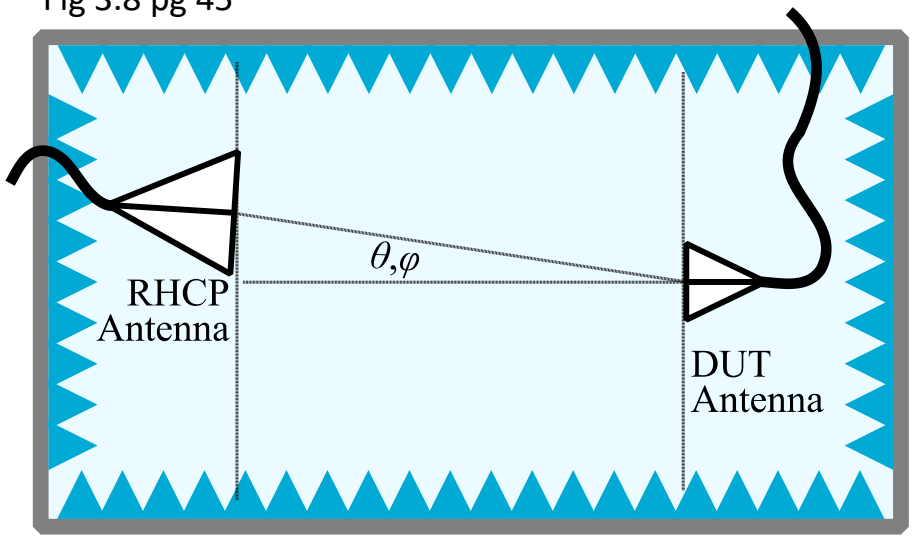
(b) NBIT Fully Anechoic Chamber

Single Source Antenna

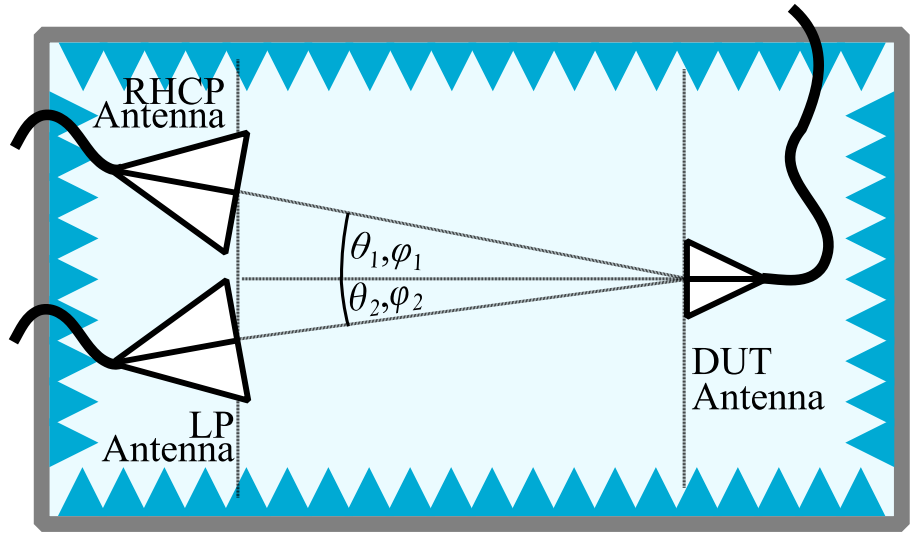
Single Right-Hand-Circularly-Polarized (RHCP) antenna setup reduces measurement uncertainties in:

- Signal-to-Interference ratio
- Source GPS antenna to source LTE antenna coupling
- Source LTE antenna to DUT antenna polarization mismatch
- Geometrical alignment

Fig 3.8 pg 45



(a) Single-antenna DUT orientation (used in this report)



(b) Two-antenna DUT orientation (used in previous work)

Calibration

Calibration product is a standard uncertainty in measurement conditions. This uncertainty informs presented data.

Calibrations take into account:

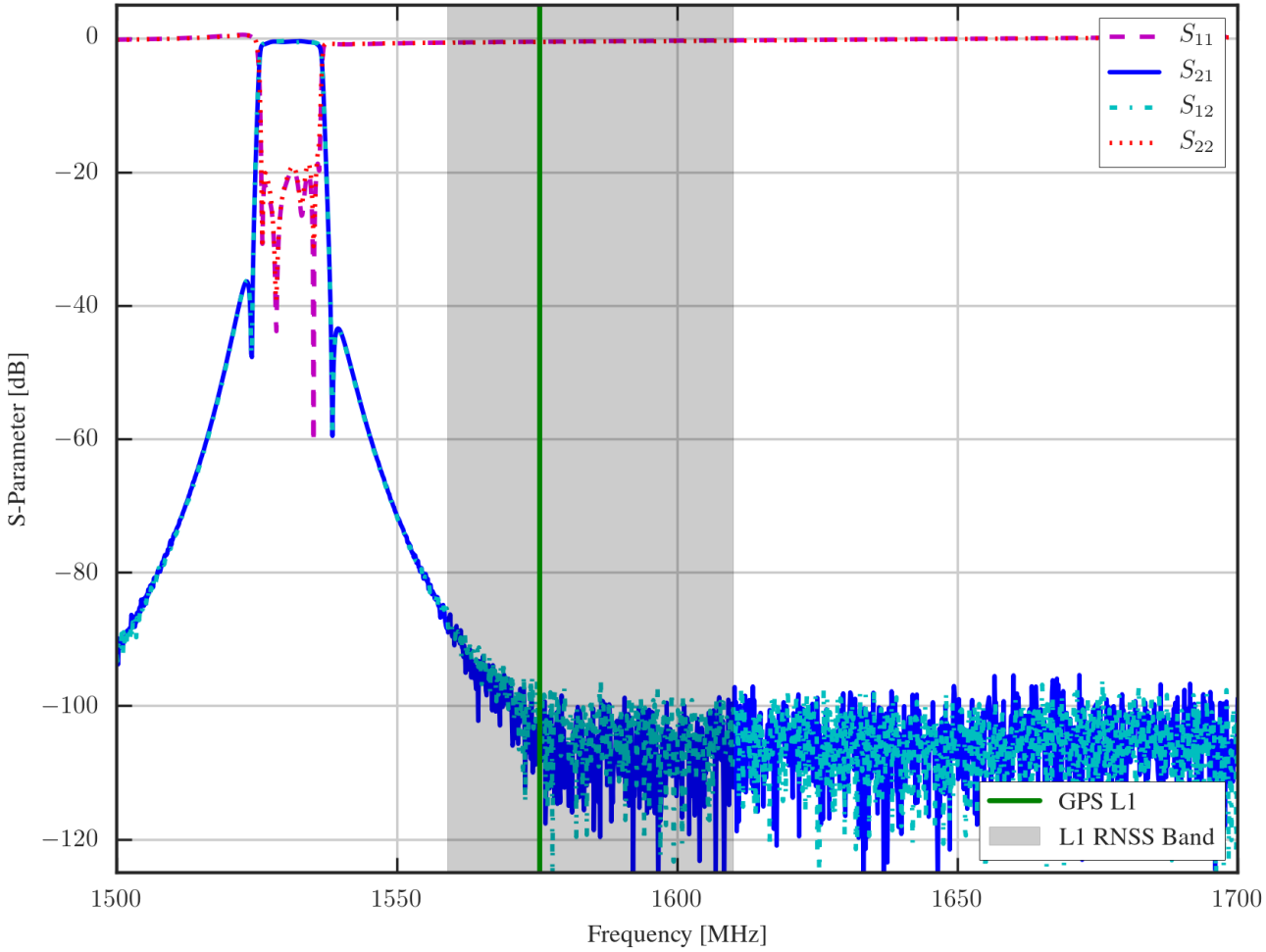
- Signal paths, antenna, DUT location, & multipath effects
- Account for 3 dB offset between linearly-polarized LTE waveform and circularly-polarized GPS waveform
- Combine GPS and LTE signals before radiation
- Lower uncertainty in the power ratio of the LTE and GPS received by the DUT

Verification Measurements

- High rejection filters
- Programmable attenuators
- Noise floor
- LTE modulation
- Testbed isolation
- Passive intermodulation
- Antenna performance
- Free space pathloss
- Signal long term stability
- Amplifier drift
- etc.

Downlink Filter

Data from Fig D.32 pg 341



Filter cutoff well below -80 dB at the beginning of the RNSS band

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Example Uncertainty Budget

Table C.19 pg 303

Table C.19: Uncertainty Budget of the LTE IB UL EIIP.

Uncertainty Classification	Uncertainty Factor	Probability Distribution	Evaluation Type	Designator	Uncertainty	Correction for Distribution	Standard Uncertainty
Antenna Calibration	Non-ideal antennas	Normal	B	U1	0.5 dB	1	0.5 dB
	Spatial variations	Normal	A	U2	0.5 dB	1	0.5 dB
	Network analyzer calibration	Normal	B	U3	0.1 dB	1	0.1 dB
	Frequency flatness	Normal	A	U4	0.2 dB	1	0.2 dB
	Non-circularity of polarization	Normal	B	U5	0.5 dB	1	0.5 dB
	Separation distance	Normal	B	U6	0.2 dB	1	0.2 dB
Instrumentation	Spectrum Analyzer	Normal	B	U7	0.5 dB	1	0.5 dB
	Long-term stability	Normal	B	U8	0.1 dB	1	0.1 dB
Testbed	Calibration	Normal	B	U9	0.14 dB	1	0.14 dB
	Amplifier drift	Normal	A	U10	0.1 dB	1	0.1 dB
	Antenna mismatch	U-shaped	B	U11	0.1 dB	0.5	0.05 dB
	Antenna connection repeatability	Normal	A	U12	0.1 dB	1	0.1 dB
	Separation distance	Normal	A	U10	0.2 dB	1	0.2 dB
	Chamber uniformity	Normal	A	U10	0.5 dB	1	0.5 dB
						Combined standard uncertainty:	**1.2 dB**
						Expanded uncertainty (k=2):	**2.4 dB**

Stepped LTE Power Tests

An LTE sweep takes numerous power level steps.

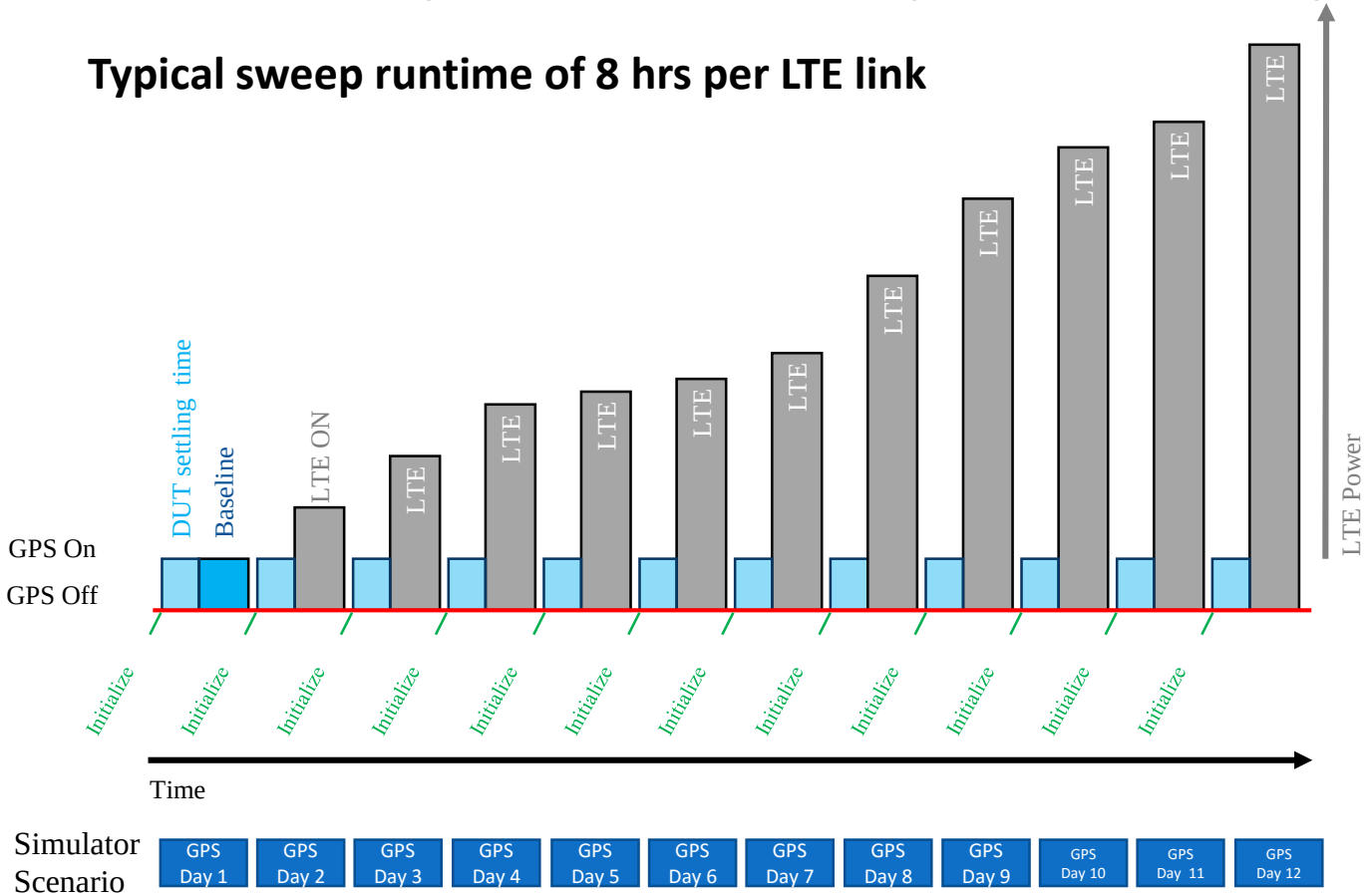

Fig. 2.5 pg 28

Each LTE power step takes 35 mins.

- **Initialize**: "cold start" if available
- **Warm up**: 15 mins without LTE

  (DUT almanac download ~ 12.5 mins)
- **LTE on**: 20 mins (ensures adequate DUT settling and warm-up)

- GPS scenarios are advanced by a modified 24 hrs.
  - Identical satellite trajectories for each power level

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Precision Location Setup

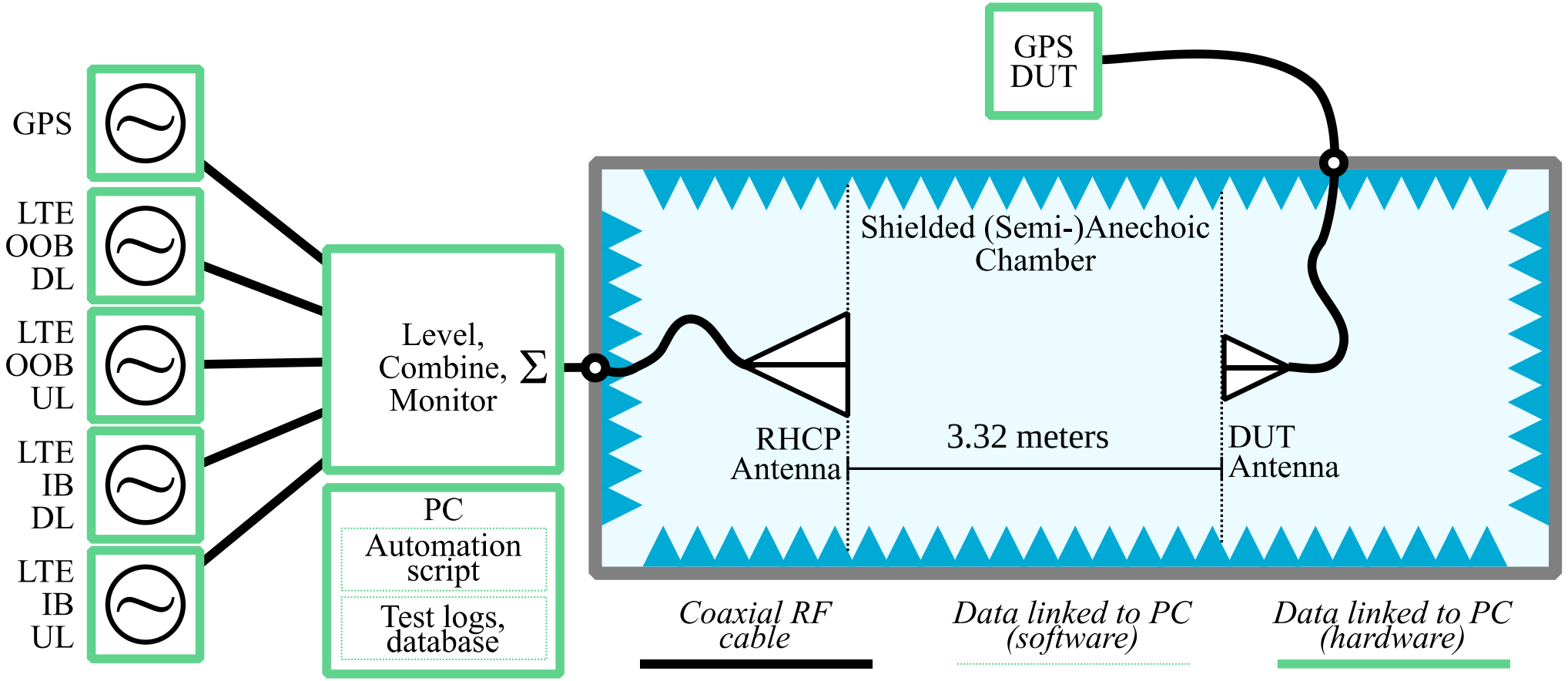


Fig. 3.2 pg 37

Real Time Kinematic Setup

Zero – Baseline Solution

- **Base** and **Rover** are subjected to the same GPS scenario.
- **Base** receives a conducted signal from the GPS simulator.
- **Base** receives an uncompromised GPS signal.
- **Rover** receives radiated GPS signal and LTE signal.

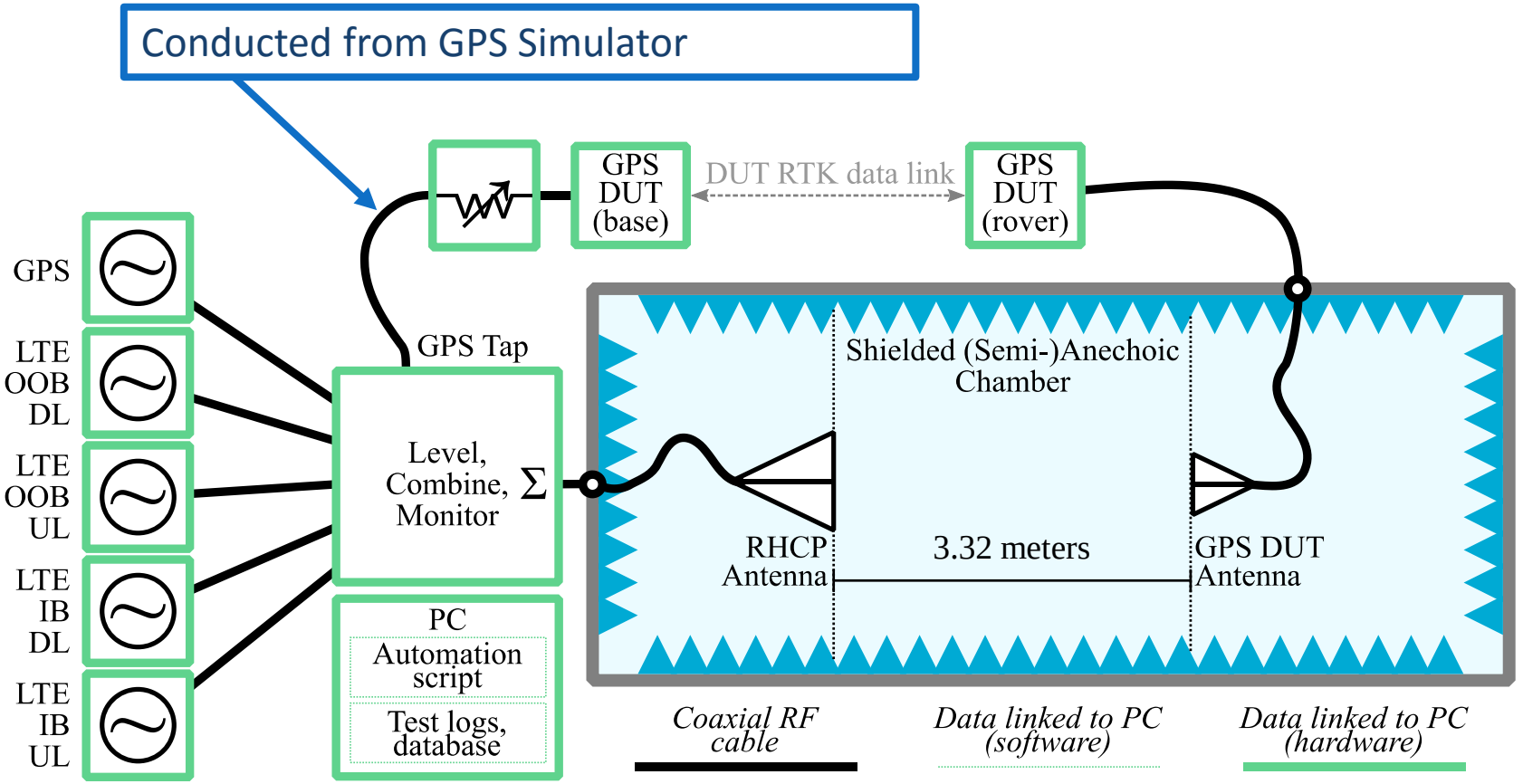


Fig. 3.3 pg 38

Additional Tests

Time-to-first-fix (TTFF)

- Types: DUT cold-start
- Collect 100 repeated measurements at each LTE power level for 2 mins (stand-alone devices) or 5 mins (RTK devices)
- If fix is not acquired, then TTFF for observation is greater than dwell-time

Time-to-first-reacquisition (TTFR)

- Types: Tunnel scenario (DUT travels between 2 points and experiences GPS dropouts)
- Collect 100 repeated measurements at each LTE power level for 2 mins (stand-alone devices)
- If fix is not acquired, then TTFR for observation is greater than dwell-time

Timing for GPSDO Receivers

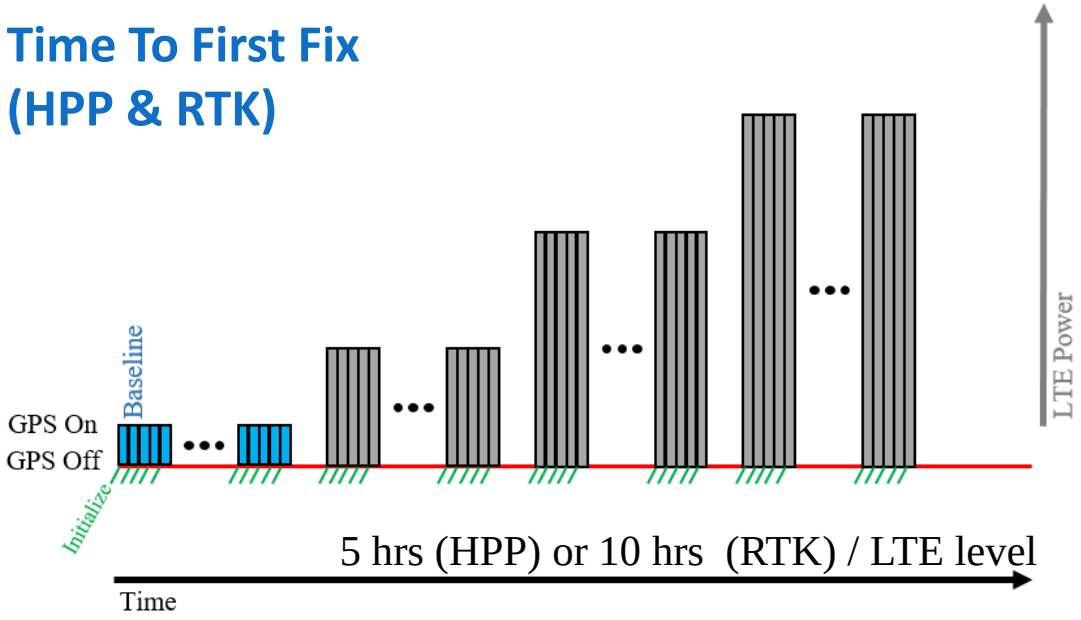
- At each LTE power level, collect measurands every second for 2.5 hours
- Measurands include satellite information, C/N_0, & 1PPS

TTFF and TTFR tests

TTFF and TTFR tests stress the DUT by acquiring fix in the presence of LTE

Fig. 2.7a pg 28

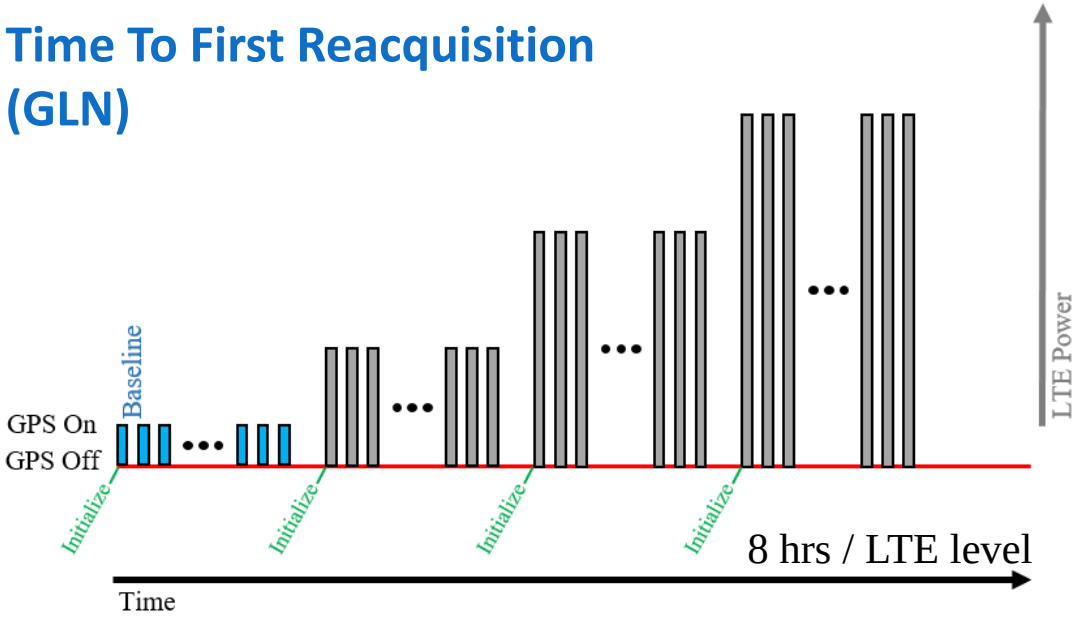
Time To First Fix (HPP & RTK)



- TTFF is measured as the time it takes to acquire a fix after a cold-start is initiated.
- The GPS simulation is reset with each cold-start/initialization command

Fig. 2.7b pg 28

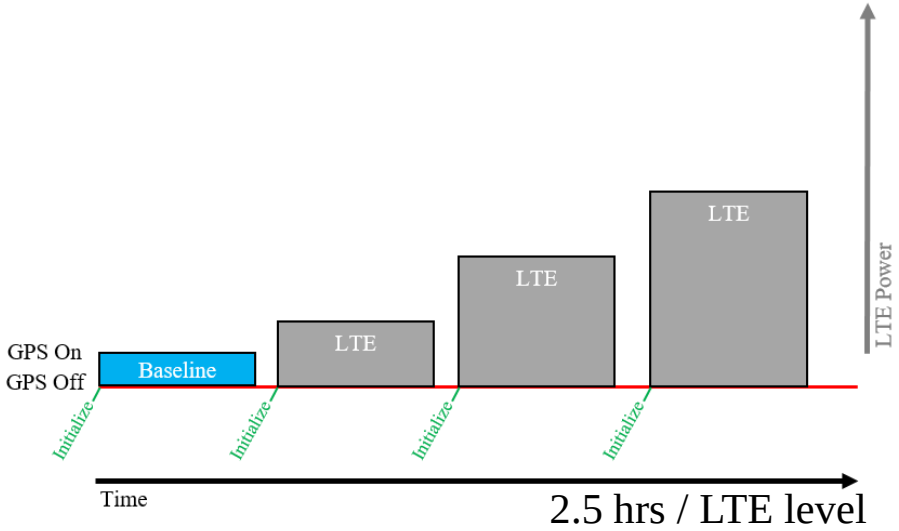
Time To First Reacquisition (GLN)



- Tunnel scenario provides for LTE power drop-outs simultaneously with a translation in position.
- TTFR is measured as the time it takes to reacquire a fix after the translation from the primary to the secondary location.
- The GPS simulation runs continuously.

Timing Tests

Fig. 2.6 pg 29



- Timing tests are performed in the presence of LTE .
- Reference clock trains the time base of the GPS Simulator and time interval counter (TIC).
- The 1PPS timing response of the DUT is compared against the reference.
- From the time deviation measurements, the Allan time deviation (TDEV) is calculated.

Timing Setup

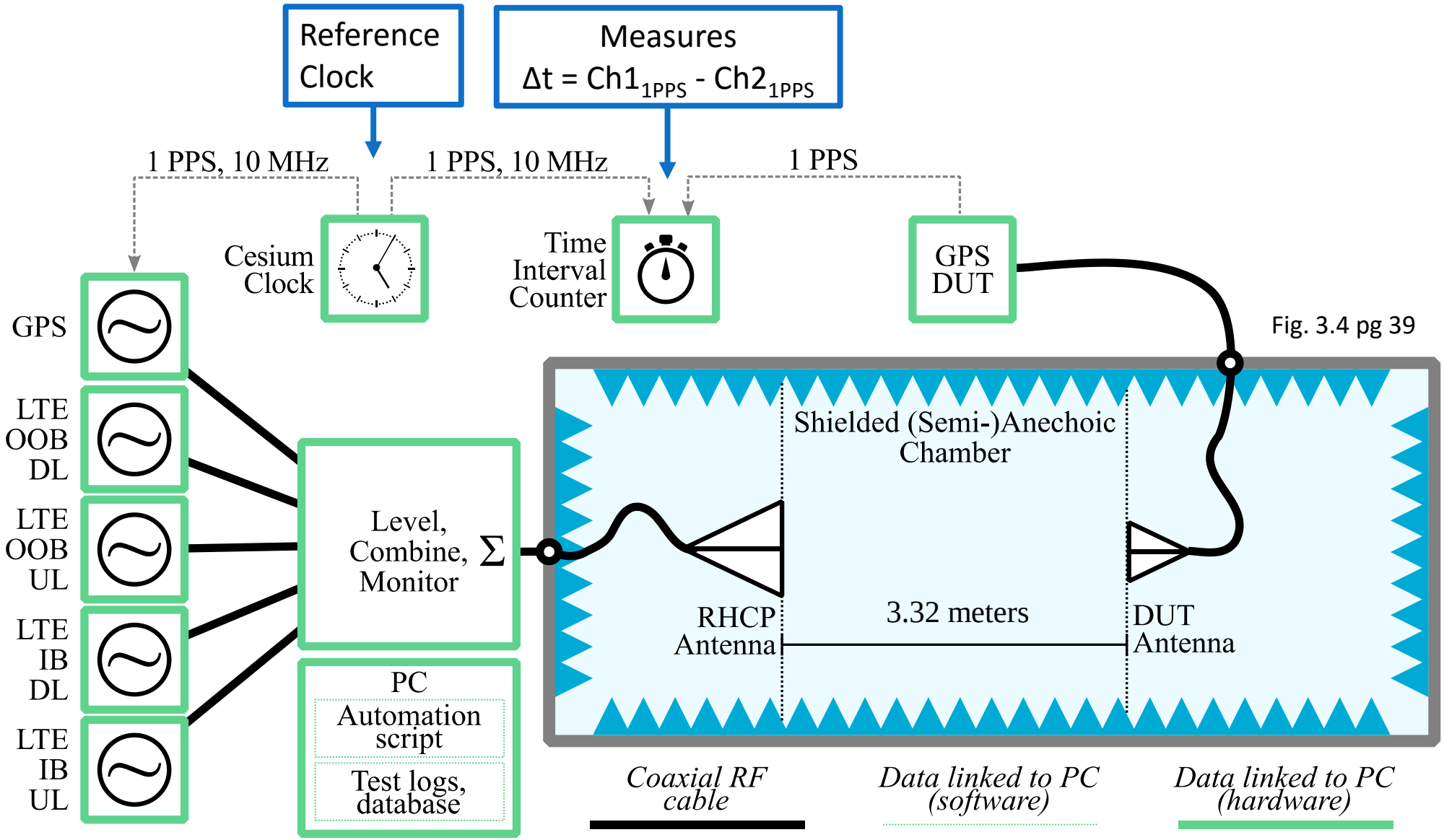


Fig. 3.4 pg 39

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Data Captures

- Diverse set of DUT data captures
- Implemented a parsing algorithm to standardize format
- Formatted data sets available to stakeholders, public, and regulators

Fig. 4.13 - 4.19 pg 88 - 91

NMEA

```
$GPGGA,015647.00,3135.89363545,N,11016.67084153,W,4,11,0.8,1381.903,M,-28.395,M,1.0,0002*4C
$PTNL,GGK,015647.00,070416,3135.89363545,N,11016.67084153,W,3,11,1.4,EHT1353.508,M*5E
$GPVTG,292.70,T,283.07,M,0.01,N,0.03,K,D*24
$GPGST,015647.00,0.000,0.003,0.003,162.7,0.003,0.003,0.006*52
$PTNL,PJK,015647.00,070416,,,,,3,11,1.4,,M*29
$PTNL,PJT,WGS84,NONE*21
$PTNL,VGK,015647.00,070416,-0000.001,-0000.001,-0000.001,3,11,1.4,M*10
$PTNL,VHD,015647.00,070416,227.134,82.636,-25.233,-65.930,0.001,-0.002,3,11,1.4,M*14
$GPGSV,4,1,13,13,30,099,45,20,86,318,44,15,35,141,44,18,32,227,44*71
$GPGSV,4,2,13,5,38,043,45,21,37,296,44,2,13,078,45,29,81,037,44*77
$GPGSV,4,3,13,12,12,179,45,25,33,209,44,26,14,314,44*49
$GPGSV,4,4,13,51,53,174,45,48,46,219,44*7E
$PTNL,AVR,015647.00,+0.0000,Yaw,+0.0000,Tilt,,,0.001,3,1.4,11*31
$GPZDA,015647.01,04,07,2016,00,00*60
$GPGSA,A,3,18,5,21,2,29,12,25,13,20,26,15,,1.4,0.8,1.2*3E
$GPRMC,015647.00,A,3135.89363545,N,11016.67084153,W,0.014,292.700,040716,9.6278,E,D*14
$PTNL,BPQ,015633.02,070416,3135.89363590,N,11016.67084096,W,EHT1353.508,M,4*7B
$GPGLL,3135.89363545,N,11016.67084153,W,015647.00,A,D*75
$GPGRS,015647.00,1,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,*61
$PFUGDP,GP,015647.00,3135.89364,N,11016.67084,W,11,9,FN,0.1,0.1,163,0.1*09
$GPGNS,015647.00,3135.89364,N,11016.67084,W,RNNNN,11,0.8,1381.9,-28.4,1.0,2*0D
```

ASCII

```
----------------------------------------------

          [m
          [mshow gnss status

  Gnss Status


  Latitude                : 31 35 53.615 N
  Longitude               : 110 16 40.250 W
  HGT Val Ellipsoid       : 1350.4 m
  HDOP                    : 0.770000
  PDOP                    : 1.430000
  Fix Quality             : 2
  Used Satellites         : 11
  Receiver Status         : Tracking
  Operation Mode          : Survey
  Antenna Status          : OK


Current GNSS Satellite View:

----------------------------------------------
|Index|GnssID|SatID|SNR  |Azimuth|Elev  |PrRes|
|-----|------|-----|-----|-------|------|-----|
|1    |GPS   |2    |42   |75     |15    |0    |
|.....|......|.....|.....|.......|......|.....|
|2    |GPS   |5    |42   |43     |42    |0    |
|.....|......|.....|.....|.......|......|.....|
|3    |GPS   |12   |42   |180    |15    |-3   |
|.....|......|.....|.....|.......|......|.....|
|4    |GPS   |13   |42   |103    |28    |2    |
|.....|......|.....|.....|.......|......|.....|
|5    |GPS   |15   |42   |144    |32    |-1   |
|.....|......|.....|.....|.......|......|.....|
|6    |GPS   |18   |42   |224    |28    |-8   |
|.....|......|.....|.....|.......|......|.....|
|7    |GPS   |20   |42   |255    |86    |7    |
|.....|......|.....|.....|.......|......|.....|
|8    |GPS   |21   |42   |292    |35    |-4   |
|.....|......|.....|.....|.......|......|.....|
|9    |GPS   |25   |42   |212    |36    |-5   |
|.....|......|.....|.....|.......|......|.....|
|10   |GPS   |26   |42   |317    |12    |-6   |
|.....|......|.....|.....|.......|......|.....|
|11   |GPS   |29   |42   |18     |78    |5    |
----------------------------------------------
```

RINEX

```
16  7 12  1 57 15.0000000  0 11G20G13G15G18G05G21G02G29G12G25G26
104952190.300 7  81780961.00844  19971738.227                19971745.9804
        43.800                25.6004
119984455.818 7  93494422.13544  22832282.391                22832291.0474
        43.200                26.2004
117247236.261 7  91361553.13144  22311414.359                22311422.9694
        44.500                26.0004
118674772.413 7  92473888.21044  22583056.508                22583065.3874
        44.000                26.6004
116281670.847 7  90609180.03044  22127677.180                22127685.5984
        44.000                26.2004
120625970.135 7  93994302.81444  22954358.281                22954366.8554
        44.100                25.0004
127252607.861 7  99157915.60244  24215366.836                24215376.2114
        43.900                25.9004
105478562.485 7  82191159.20544  20071911.891                20071920.0314
        43.700                25.8004
129030062.009 7 100542955.53844  24553607.227                24553617.5864
        43.900                26.4004
119420196.379 7  93054756.02444  22724912.594                22724921.6994
        44.000                25.2004
128519828.357 7 100145393.33844  24456516.609                24456526.4224
        43.700                26.1004
```

ASCII + NMEA

```
0,1B
186:01:39:03
$GPGLL,3135.8930,N,11016.6706,W,013903.340,A*38V=10 S=18 T=10 P=OFF E=00
L U=00 S=OFF
S2 P3 F00002 #00001 T2016:186:01:37:54 W110:16:40.238 N31:35:53.581 H+01363.75
I=03:00 X=ff:ff
```

ASCII

```
          16-07-04 02:32:51
M  101 COMPLD
   "GPS:LAT=31 35.893N,LONG=110 16.670W,ALT=1380.50,UTC=2-32-51,
   MODE=AUTO, MERIT=1024NS, SUCCESS=32%
   SAT-29, USE=Y, CNO=47, ELEV=74, AZ=130, LOCK=1677,
   SAT-20, USE=Y, CNO=47, ELEV=71, AZ=21, LOCK=459,
   SAT-15, USE=N, CNO=46, ELEV=47, AZ=124, LOCK=0,
   SAT-21, USE=Y, CNO=46, ELEV=46, AZ=312, LOCK=131,
   SAT-18, USE=Y, CNO=46, ELEV=45, AZ=239, LOCK=20,
   SAT-13, USE=Y, CNO=46, ELEV=34, AZ=80, LOCK=138,
   SAT-5, USE=Y, CNO=46, ELEV=24, AZ=45, LOCK=560,
   SAT-25, USE=Y, CNO=46, ELEV=19, AZ=200, LOCK=205,
   SAT-26, USE=Y, CNO=47, ELEV=19, AZ=300, LOCK=20,
   SAT-10, USE=N, CNO=46, ELEV=10, AZ=231, LOCK=0,
"
   /* LINK: 3, CMD: RTRV-GPS-STAT::GPS:101 */
;RTRV-GPS-STAT::GPS:101;
```

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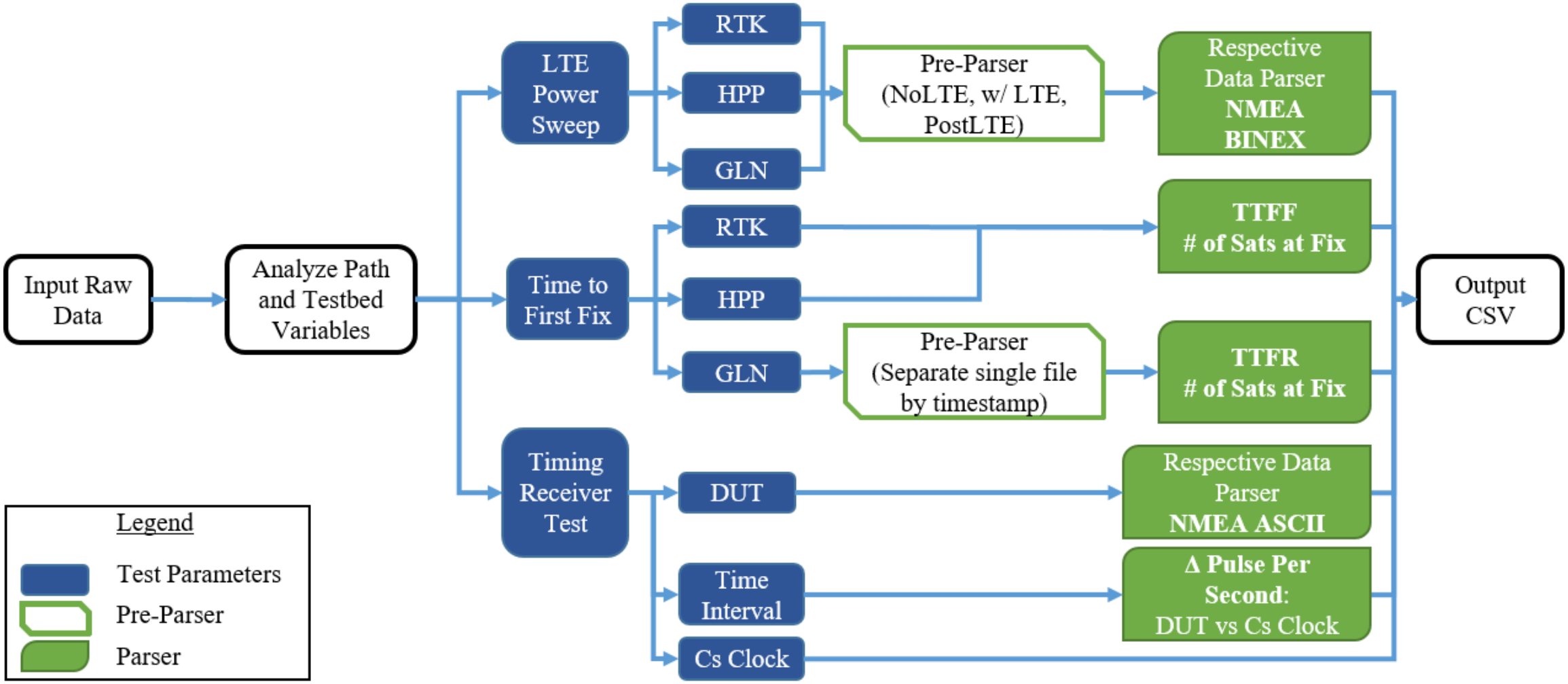
Data Parsing

Fig. 5.1 pg 94



Example Parsed Data Output

- Testbed State File:

Test Run	GPS Attenuator Gain	GPS Simulator UTC Time	LTE IB DL Amplifier rf output enable	LTE IB DL Attenuator gain	LTE IB DL Synthesizer rf output enable	LTE IB UL Attenuator gain	LTE_IB_UL Synthesizer rf output enable	LTE OOB DL Attenuator gain	LTE OOB DL Synthesizer rf output enable	LTE OOB UL Attenuator gain	LTE OOB UL Synthesizer rf output enable	PC local time
3	-33.75	7/7/2016 1:50:22	TRUE	-55	TRUE	-110	TRUE	-55	TRUE	-110	TRUE	8/3/2016 20:27:54

- Raw Data Sentence:

```
$GPGGA,015022.00,3135.8936,N,11016.6708,W,1,11,0.8,1380.50,M,-28.50,M,,*61
```

- Final Data Output:

Date Time	LTE power dBm	Stdev LTE power dB	Fix	Sats In View	Longitude deg	Longitude truth deg	Latitude deg	Latitude truth deg	Altitude meters	Altitude truth meters
7/7/2016 1:50:22	-67.1	1.2	1	11	31.598227	31.598227	-110.27785	-110.27785	1351.8964	1352.3

ECEFx meters	ECEFx truth meters	ECEFy meters	ECEFy truth meters	ECEFz meters	ECEFz truth meters	positionError3D meters
-1884901	-1884901	-5101612	-5101612	3323277	3323277	0.405502

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Data Publication

- 3859 CSV files (780 MB)
  - Request data DVD via form submission

  https://www.nist.gov/programs-projects/impact-lte-signals-gps-receivers
- Readme files with detailed descriptions of file contents
- Anonymized data sets
  - GPS simulator truth files
  - Baseline data
  - Stepped LTE power sweeps
  - TTFF & TTFR tests
  - Timing tests

Readme

This directory contains files consisting of processed test data from the NASCTN "LTE Impacts on GPS" project. A summary of file contents can be found in Section 5.6 of the Final Test Report and also in CSV_header_information.xlsx that accompanies this data. The data provided here was processed from raw form with the parsing and data wrangling steps described in Chapter 5 of the Final Test Report. For details on the types of tests performed, see the Final Test Report.

Important Acronyms

GLN – General Navigation and Location devices

HPP – High Precision Positioning devices

RTK – Real Time Kinematic devices

GPSDO – GPS Disciplined Oscillator devices also referred to as the timing devices

EIIP – Equivalent Isotropic Incident Power

IB – In Band, refers to the in-band spectral component of the proposed emissions mask

OOB – Out Of Band, refers to the out of band emissions of the proposed emissions mask

DL – Downlink (1526 - 1536 MHz)

UL1 – Uplink 1 (1627.5 - 1637.5 MHz)

UL2 – Uplink 2 (1646.5 - 1656.5 MHz)

Combo – combination of Downlink signal (held constant at -50dBm, or where otherwise indicated in the plane of the receiver) and Uplink 1 signal (power is varied). The LTE power level given in the "*.csv" files is the aggregate signal power in the plane of the DUT.

TTFF – Time To First Fix (implies a cold-start reset at the beginning of the acquisition). If time is greater than allotted time a NAN is printed in the TTFF column. This test was conducted for HPP, RTK, and DEV units.

TTFR – Time to First Reacquisition (the DUT experiences a Loss of Lock for 3 minutes and then the GPS signal is reintroduced, the TTFR is the time it takes for the DUT to reacquire lock). If time is greater than allotted time a NAN is printed in the TTFR column. -This test applied to GLN units only.

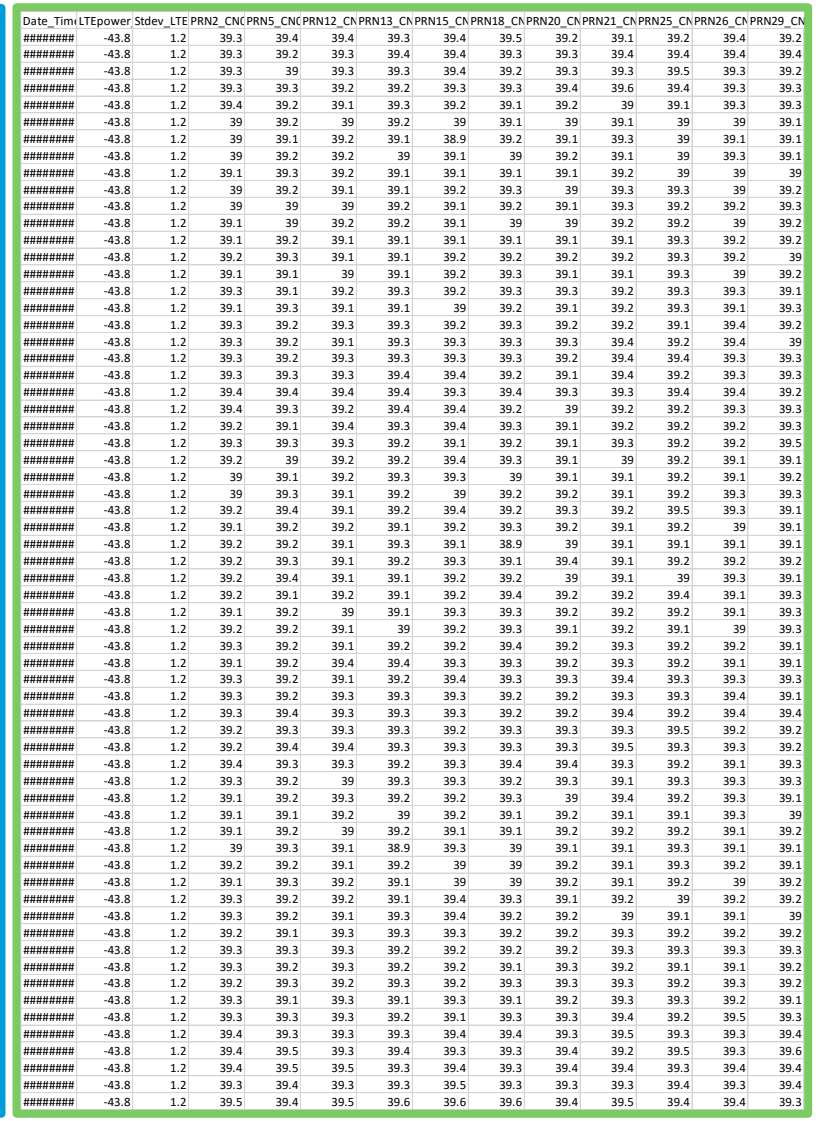
Timing – GPS Disciplined Oscillator (Timing receiver tests), note that timing tests did not have a no-LTE soak period built in and the DUT had to acquire lock in the presence of the LTE signal.

Notes

The files are organized in a nested directory structure, where the directory levels correspond to test type, device class & LTE type, and DUT number, respectively. For the LTE power sweep tests, one data file is provided for each LTE power level. By contrast, for TTFF and TTFR tests, the data for all tests of a given DUT are listed in a single file.

For example, data for DUT 8 from an UL1 LTE power sweep test under the nominal GPS scenario is found with the following folder hierarchy:

LTEpower_sweeps-nominal→HPP-UL1 →DUT8 →level_#_"measurand".csv.



Date_Tim	LTEpower	Stdev_LTE	PRN2_CN	PRN5_CN	PRN12_CN	PRN13_CN	PRN15_CN	PRN18_CN	PRN20_CN	PRN21_CN	PRN25_CN	PRN26_CN	PRN29_CN
########	-43.8	1.2	39.3	39.4	39.4	39.3	39.4	39.5	39.2	39.1	39.2	39.4	39.2
########	-43.8	1.2	39.3	39.2	39.3	39.4	39.4	39.3	39.3	39.4	39.4	39.4	39.4
########	-43.8	1.2	39.3	39	39.3	39.3	39.4	39.2	39.3	39.3	39.5	39.3	39.2
########	-43.8	1.2	39.3	39.3	39.2	39.2	39.3	39.3	39.4	39.6	39.4	39.3	39.3
########	-43.8	1.2	39.4	39.2	39.1	39.3	39.2	39.1	39.2	39	39.1	39.3	39.3
########	-43.8	1.2	39	39.2	39	39.2	39	39.1	39	39.1	39	39	39.1
########	-43.8	1.2	39	39.1	39.2	39.1	38.9	39.2	39.1	39.3	39	39.1	39.1
########	-43.8	1.2	39	39.2	39.2	39	39.1	39	39.2	39.1	39	39.3	39.1
########	-43.8	1.2	39.1	39.3	39.2	39.1	39.1	39.1	39.1	39.2	39	39	39
########	-43.8	1.2	39	39.2	39.1	39.1	39.2	39.3	39	39.3	39.3	39	39.2
########	-43.8	1.2	39	39	39	39.2	39.1	39.2	39.1	39.3	39.2	39.2	39.3
########	-43.8	1.2	39.1	39	39.2	39.2	39.1	39	39	39.2	39.2	39	39.2
########	-43.8	1.2	39.1	39.2	39.1	39.1	39.1	39.1	39.1	39.1	39.3	39.2	39.2
########	-43.8	1.2	39.2	39.3	39.1	39.1	39.2	39.2	39.2	39.2	39.3	39.2	39
########	-43.8	1.2	39.1	39.1	39	39.1	39.2	39.3	39.1	39.1	39.3	39	39.2
########	-43.8	1.2	39.3	39.1	39.2	39.3	39.2	39.3	39.3	39.2	39.3	39.3	39.1
########	-43.8	1.2	39.1	39.3	39.1	39.1	39	39.2	39.1	39.2	39.3	39.1	39.3
########	-43.8	1.2	39.3	39.2	39.3	39.3	39.2	39.3	39.2	39.2	39.1	39.4	39.2
########	-43.8	1.2	39.3	39.2	39.1	39.3	39.3	39.3	39.3	39.4	39.2	39.4	39
########	-43.8	1.2	39.3	39.2	39.3	39.3	39.3	39.3	39.2	39.4	39.4	39.3	39.3
########	-43.8	1.2	39.3	39.3	39.3	39.4	39.4	39.2	39.1	39.4	39.2	39.3	39.3
########	-43.8	1.2	39.4	39.4	39.4	39.4	39.3	39.4	39.3	39.3	39.4	39.4	39.2
########	-43.8	1.2	39.4	39.3	39.2	39.4	39.4	39.2	39	39.2	39.2	39.3	39.3
########	-43.8	1.2	39.2	39.1	39.4	39.3	39.4	39.3	39.1	39.2	39.2	39.2	39.3
########	-43.8	1.2	39.3	39.3	39.3	39.2	39.1	39.2	39.1	39.3	39.2	39.2	39.5
########	-43.8	1.2	39.2	39	39.2	39.2	39.4	39.3	39.1	39	39.2	39.1	39.1
########	-43.8	1.2	39	39.1	39.2	39.3	39.3	39	39.1	39.1	39.2	39.1	39.2
########	-43.8	1.2	39	39.3	39.1	39.2	39	39.2	39.2	39.1	39.2	39.3	39.3
########	-43.8	1.2	39.2	39.4	39.1	39.2	39.4	39.2	39.3	39.2	39.5	39.3	39.1
########	-43.8	1.2	39.1	39.2	39.2	39.1	39.2	39.3	39.2	39.1	39.2	39	39.1
########	-43.8	1.2	39.2	39.2	39.1	39.3	39.1	38.9	39	39.1	39.1	39.1	39.1
########	-43.8	1.2	39.2	39.3	39.1	39.2	39.3	39.1	39.4	39.1	39.2	39.2	39.2
########	-43.8	1.2	39.2	39.4	39.1	39.1	39.2	39.2	39	39.1	39	39.3	39.1
########	-43.8	1.2	39.2	39.1	39.2	39.1	39.2	39.4	39.2	39.2	39.4	39.1	39.3
########	-43.8	1.2	39.1	39.2	39	39.1	39.3	39.3	39.2	39.2	39.2	39.1	39.3
########	-43.8	1.2	39.2	39.2	39.1	39	39.2	39.3	39.1	39.2	39.1	39	39.3
########	-43.8	1.2	39.3	39.2	39.1	39.2	39.2	39.4	39.2	39.3	39.2	39.2	39.1
########	-43.8	1.2	39.1	39.2	39.4	39.4	39.3	39.3	39.2	39.3	39.2	39.1	39.1
########	-43.8	1.2	39.3	39.2	39.1	39.2	39.4	39.3	39.3	39.4	39.3	39.3	39.3
########	-43.8	1.2	39.3	39.2	39.3	39.3	39.3	39.2	39.2	39.3	39.3	39.4	39.1
########	-43.8	1.2	39.3	39.4	39.3	39.3	39.3	39.2	39.2	39.4	39.2	39.4	39.4
########	-43.8	1.2	39.2	39.3	39.1	39.2	39.3	39.2	39.3	39.3	39.5	39.2	39.2
########	-43.8	1.2	39.2	39.4	39.4	39.3	39.3	39.3	39.3	39.5	39.3	39.3	39.2
########	-43.8	1.2	39.4	39.3	39.3	39.2	39.4	39.3	39.4	39.2	39.4	39.1	39.3
########	-43.8	1.2	39.3	39.2	39.1	39.3	39.3	39.3	39.2	39.3	39.3	39.2	39.3
########	-43.8	1.2	39.3	39.4	39.4	39.3	39.3	39.3	39.4	39.3	39.3	39.4	39.1
########	-43.8	1.2	39.3	39.4	39.4	39.3	39.2	39.3	39.2	39.4	39.4	39.4	39.4
########	-43.8	1.2	39.2	39.3	39.4	39.3	39.2	39.3	39.3	39.3	39.5	39.2	39.2
########	-43.8	1.2	39.2	39.4	39.4	39.3	39.3	39.3	39.3	39.5	39.3	39.3	39.2
########	-43.8	1.2	39.4	39.3	39.2	39.3	39.4	39.3	39.4	39.3	39.2	39.1	39.2
########	-43.8	1.2	39.4	39.2	39.3	39.2	39.3	39.2	39.3	39.3	39.2	39.3	39.2
########	-43.8	1.2	39.3	39.1	39.3	39.1	39.3	39.1	39.2	39.3	39.3	39.2	39.1
########	-43.8	1.2	39.3	39.3	39.3	39.2	39.1	39.3	39.3	39.4	39.2	39.5	39.3
########	-43.8	1.2	39.4	39.3	39.3	39.3	39.4	39.4	39.3	39.5	39.3	39.3	39.4
########	-43.8	1.2	39.4	39.5	39.3	39.4	39.3	39.3	39.4	39.2	39.5	39.3	39.6
########	-43.8	1.2	39.4	39.5	39.5	39.3	39.4	39.3	39.4	39.4	39.3	39.4	39.4
########	-43.8	1.2	39.3	39.4	39.3	39.3	39.5	39.3	39.3	39.3	39.4	39.3	39.4
########	-43.8	1.2	39.5	39.4	39.5	39.6	39.6	39.6	39.4	39.5	39.4	39.4	39.3

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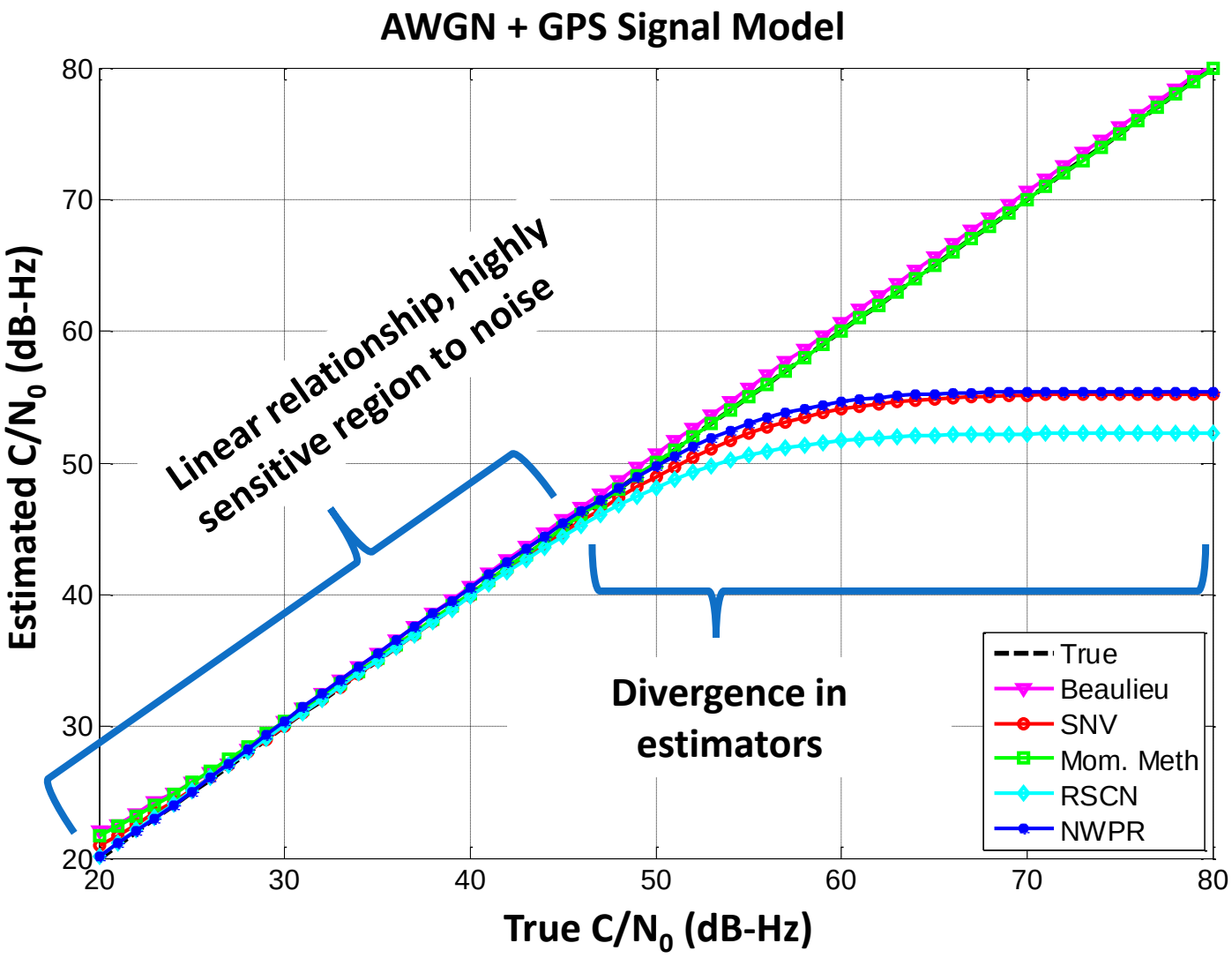
Simulation Study of C/N_0 Estimators

- Variability in C/N_0 reported by DUTs includes
  - Intra-DUT variations due to intrinsic DUT performance and changing conditions
    - Enables inferences about individual DUT performance
    - Evaluated by our data analysis
  - Inter-DUT variations due to choice of C/N_0 estimation method implemented by DUT
    - Because each DUT is a “black box”, the estimation algorithm is unknown
    - Enables inferences about a population of DUTs
    - Not included in our data analysis
- We carried out a limited simulation study to shed light on the second component
  - Appendix B in Final Report

Bias in C/N_0 estimation algorithms



Reproduction of Figure 3 in Falletti et. al., IEEE Trans. Aerosp. Electron. Syst., vol 47, no 1, Jan 2011

Estimators:

- Beaulieu's method
- Signal-to-Noise Variance (SNV)
- Moments method (MM)
- Real Signal-Complex Noise (RSCN)
- Narrowband-Wideband Power Ratio Method (NWPR)

Simulation Study Summary

- Compared five estimators studied in (Falletti et al., 2011):
  - Beaulieu's method
  - Signal-to-noise variance (SNV)
  - Moments method (MM)
  - Real signal-complex noise (RSCN)
  - Narrowband-wideband power ratio (NWPR) method
- Building on (Falletti et al., 2011) signal model,
  - Modeled adjacent-band LTE UL1 and associated OOBE as in physical testing
  - Used a Rician fading model for the GPS channel
  - Simulated 2000 Monte Carlo trials for each set of parameters
  - Inter-algorithm variability evaluated by comparing histograms

Example Results

True C/N_0 = 40 dB-Hz & LTE UL1 EIIP = -40 dBm

AWGN GPS channel

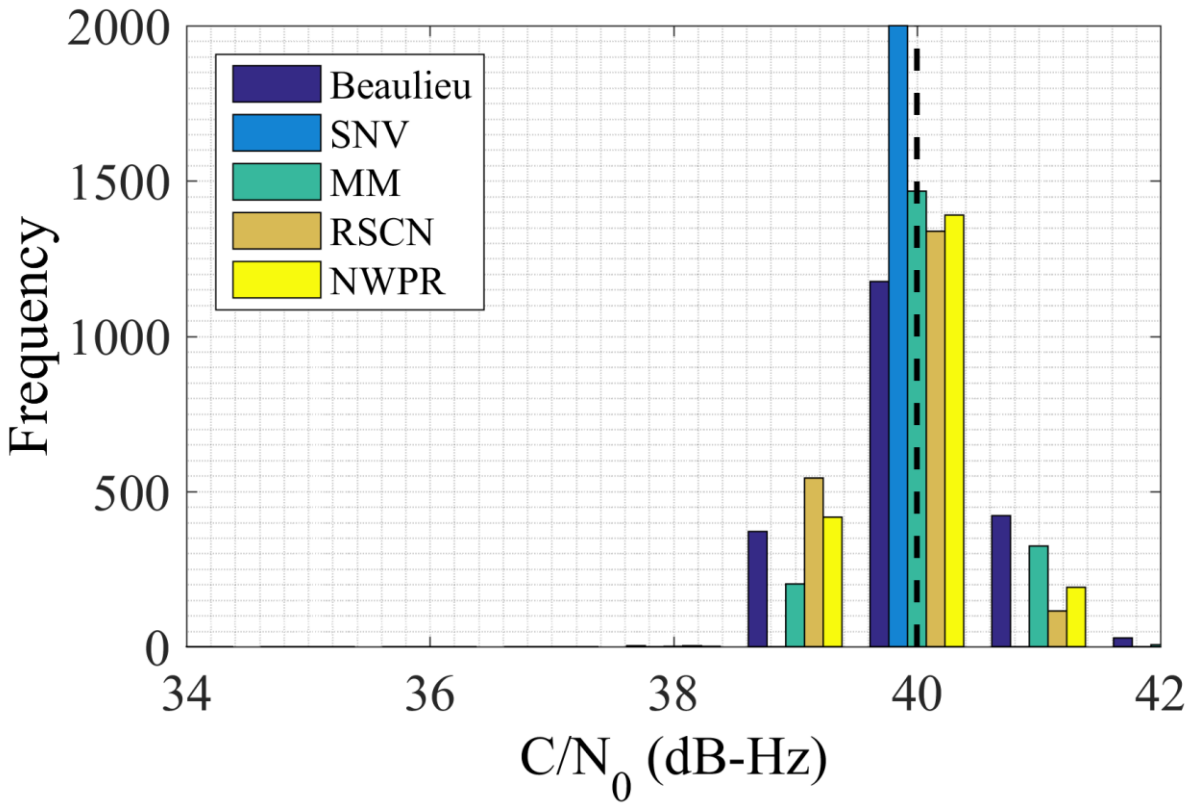


Fig. B.1 – pg. 274

Rician GPS channel

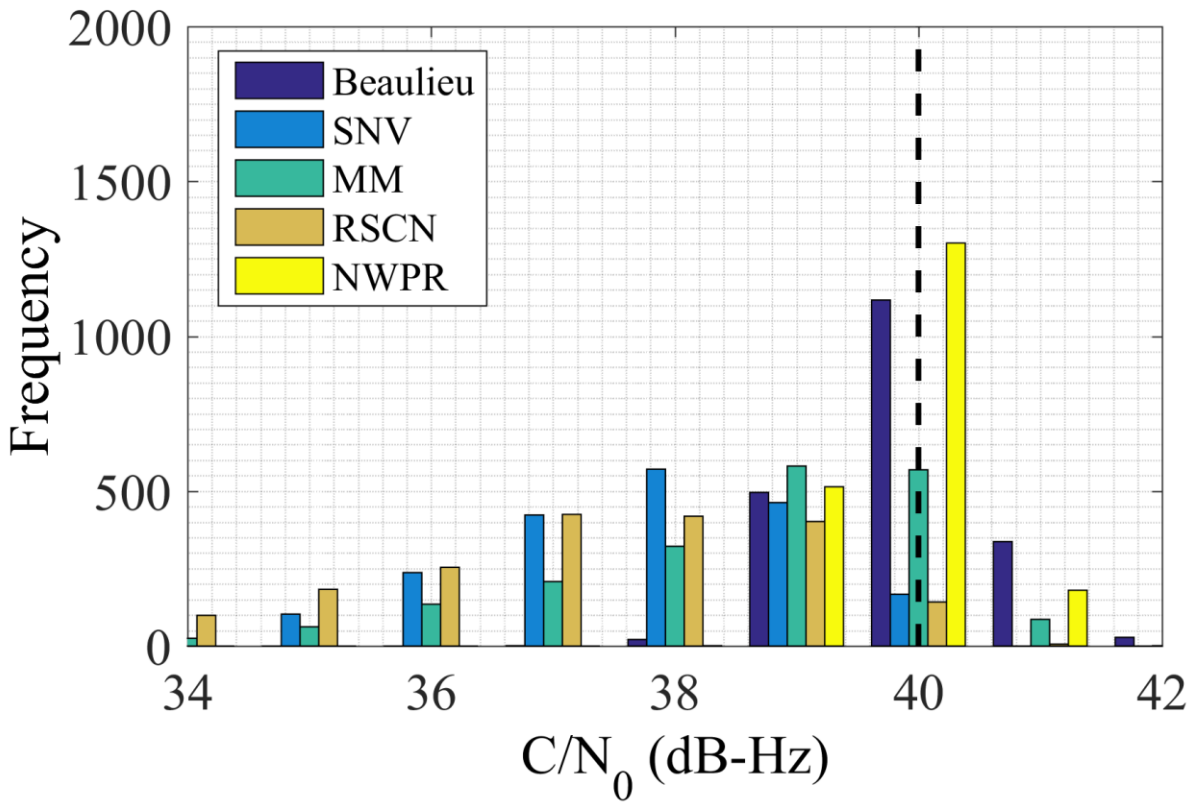


Fig. B.2 – pg. 275

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Break

Data Analysis for LTE Power Sweep Tests

- Scatterplots for 3D position error, C/N_0, and number of satellites in view
- Plots of median steady-state 3D position error & C/N_0
  - Each time-series assumed to reach a steady-state condition

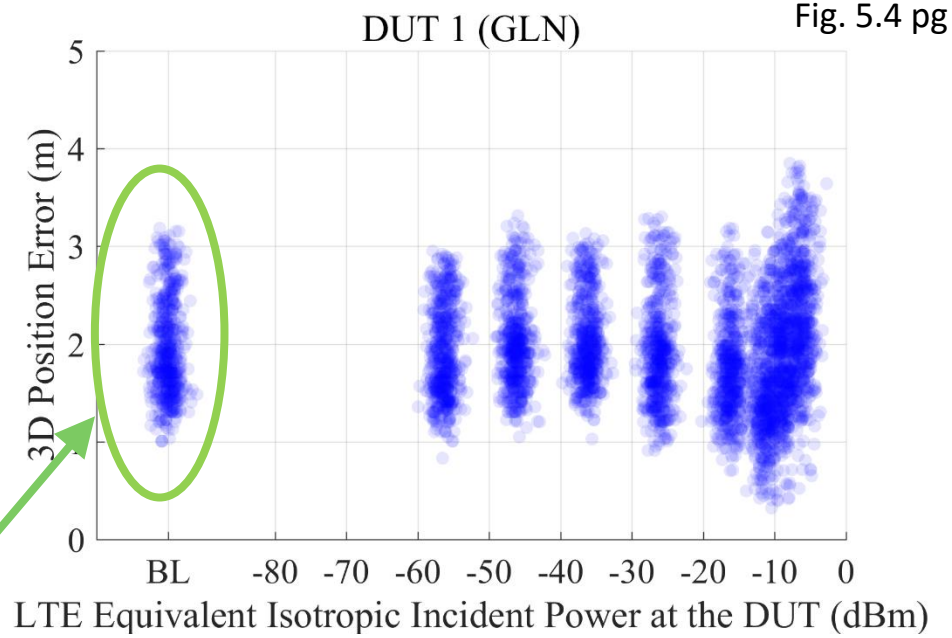
Pre-Analysis Processing:

- Obtain 3D position error time-series
  - Convert latitude, longitude & altitude to Cartesian ECEF (earth-centered, earth-fixed) coordinates
  - Calculate Euclidean distance between true and reported position
- Reduce C/N_0 to scalar time-series
  - For each time point, find median C/N_0 across reported GPS satellites
    - Median is robust to outliers

Baseline

- Baseline (BL) tests show steady-state behavior of devices without LTE transmissions.
- Statistical comparisons are made against the baseline.

Fig. 5.4 pg 109



No LTE power

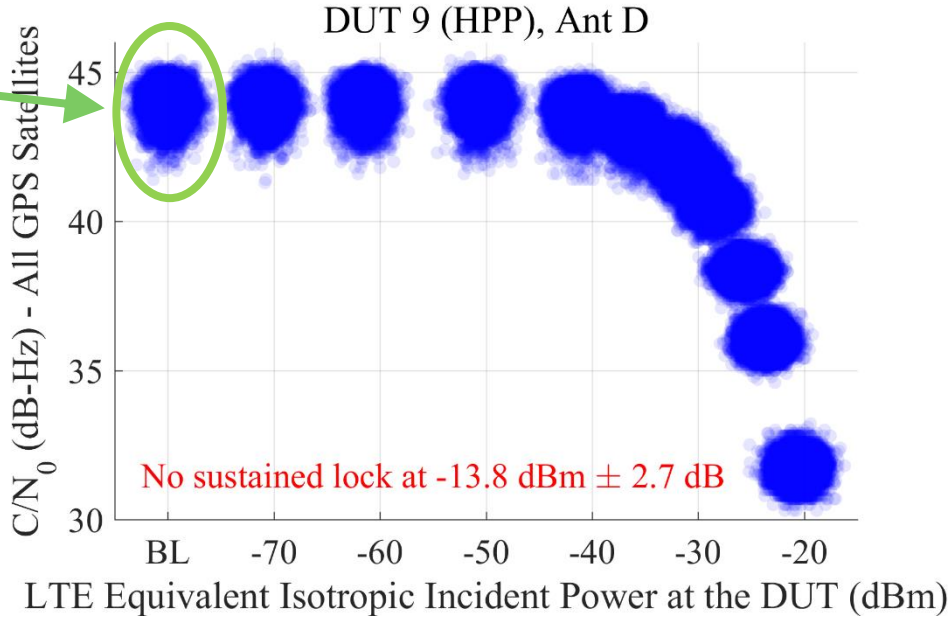


Fig. 5.5 pg 110

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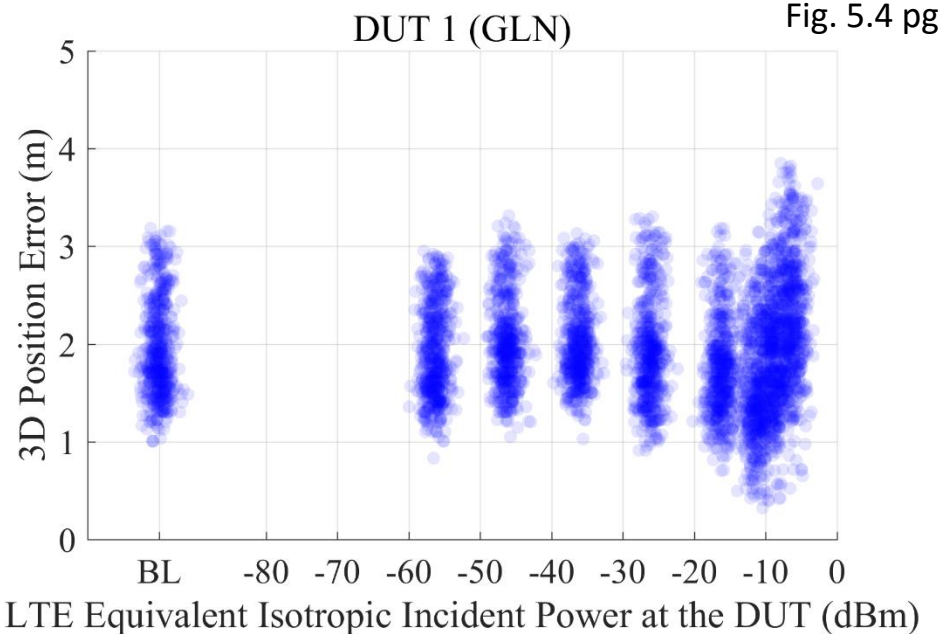
Raw Data - Scatter Plots

- "BL" indicates baseline
- Horizontal coordinate randomly generated from the estimated distribution for LTE EIIP
  - Communicates uncertainty in LTE power
  - Aids visualization (Point Clouds)
- Time-dependent nature of data is not conveyed

Fig. 5.4 pg 109



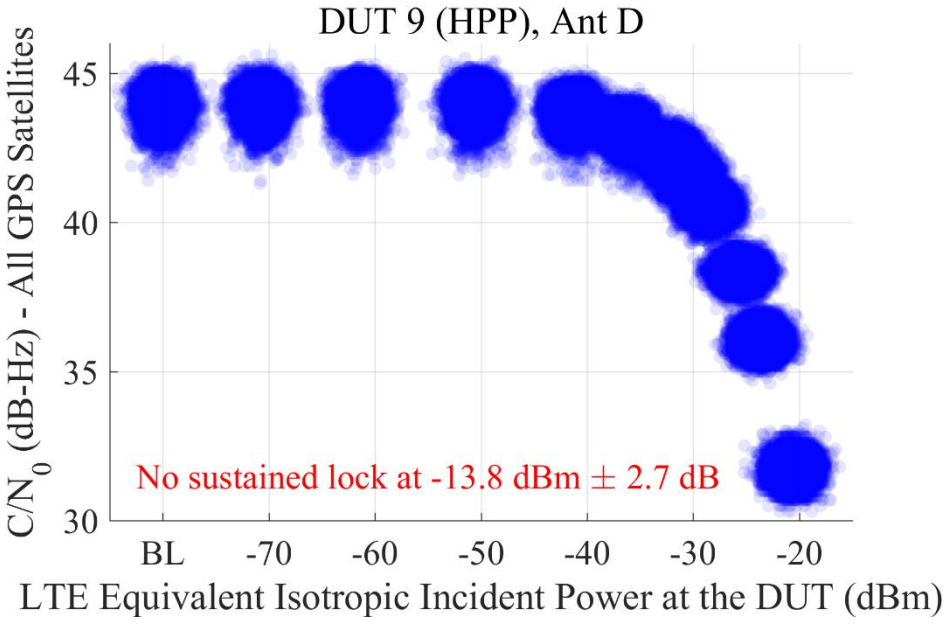


Fig. 5.5 pg 110

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Examples of Steady-State Median Plots

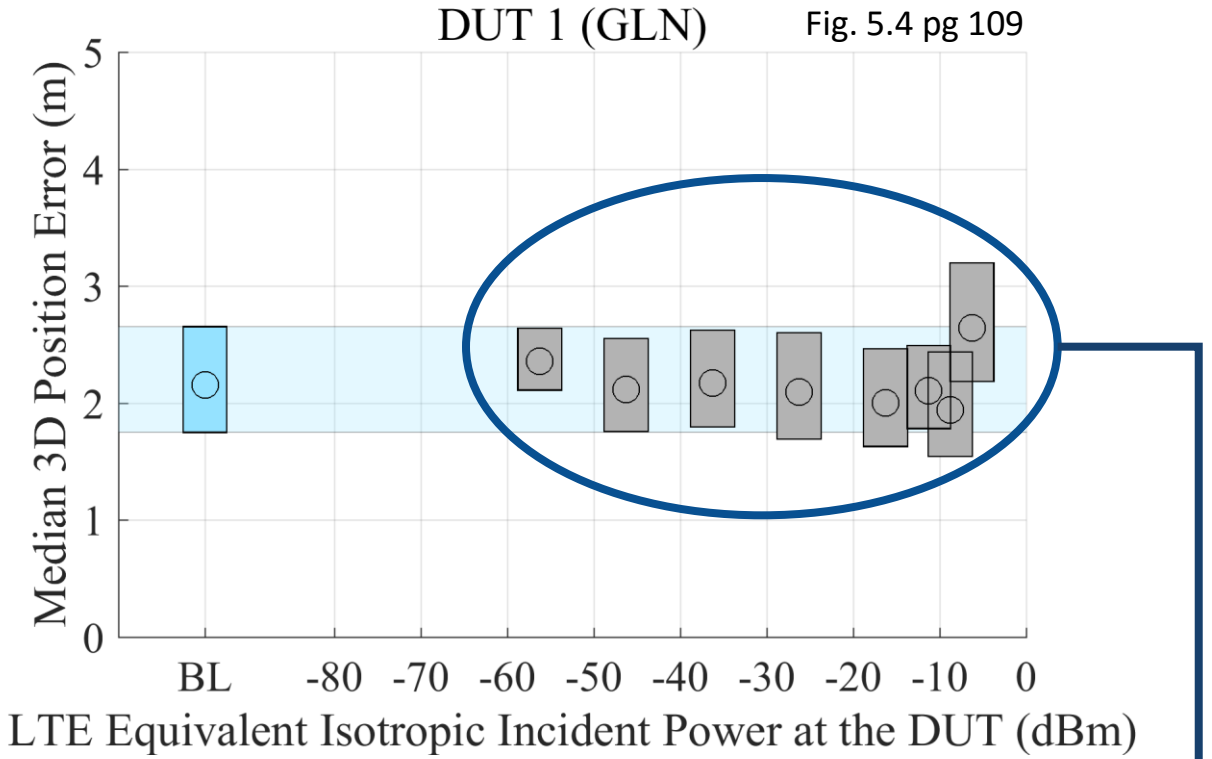

Fig. 5.4 pg 109

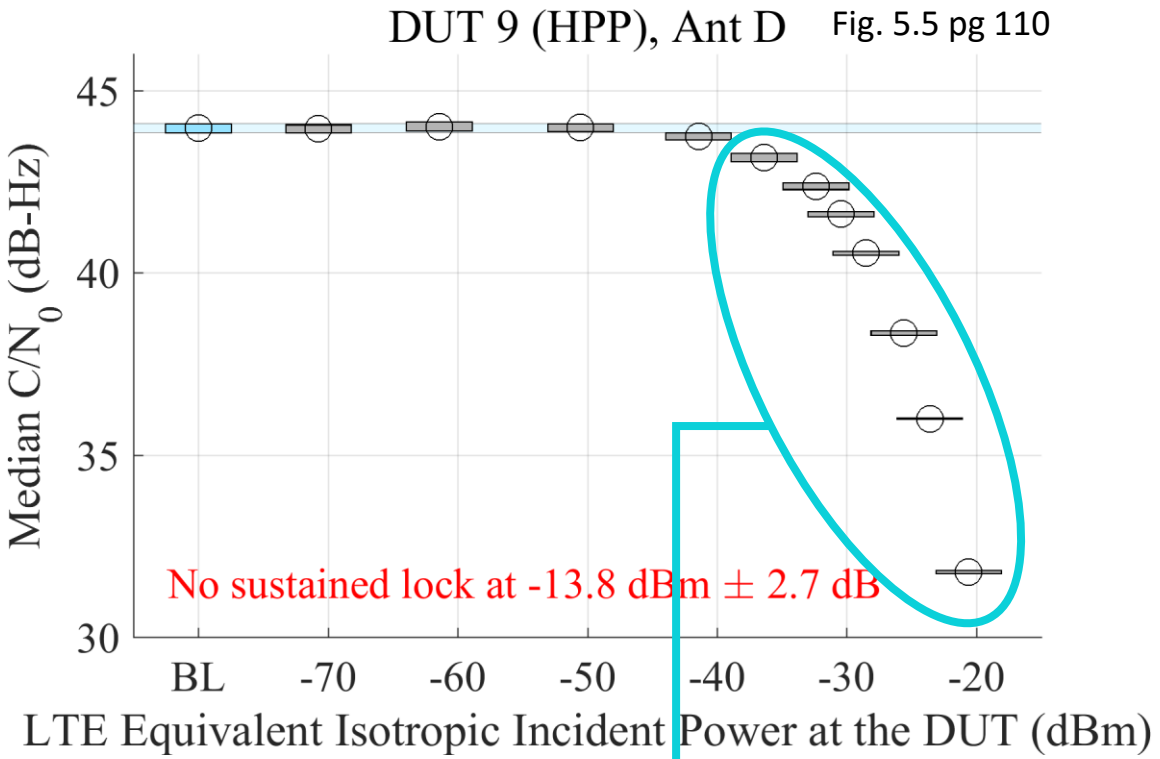

Fig. 5.5 pg 110

Baseline (BL) – No LTE Power

Overlapping with the confidence bound of the baseline – No statistically significant difference

Statistically significant difference

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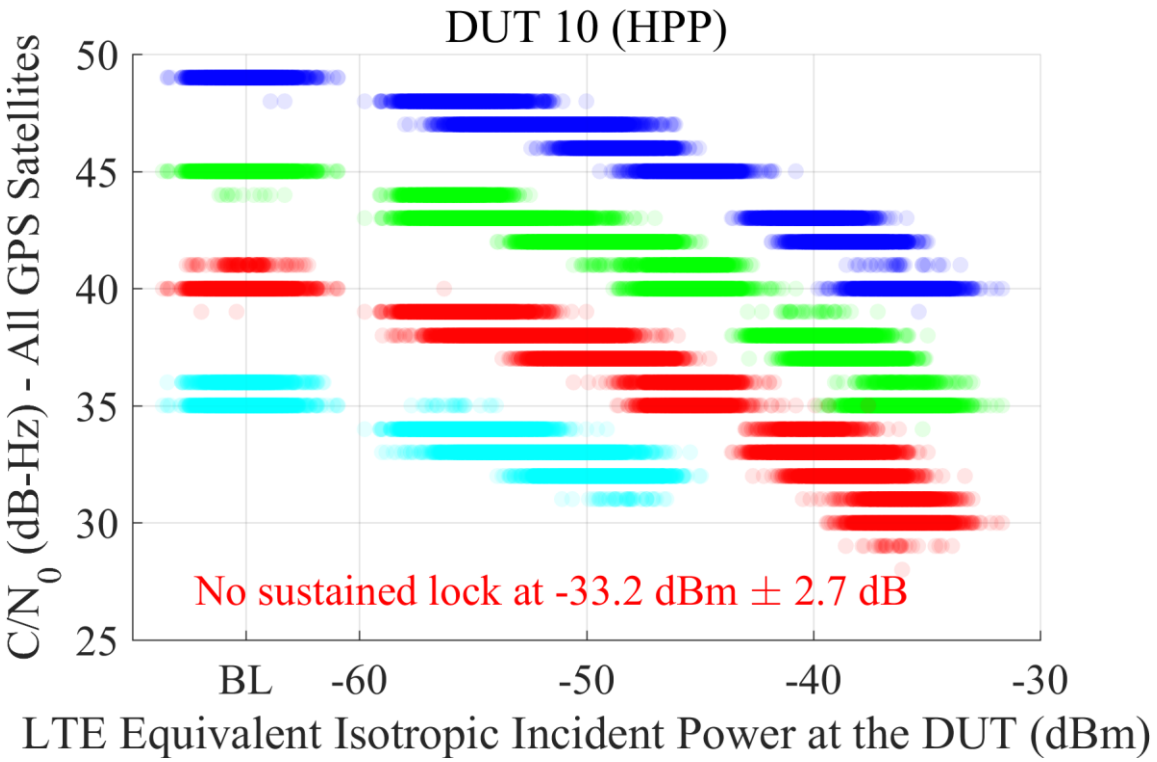
Limited Scenario: C/N_0 plots



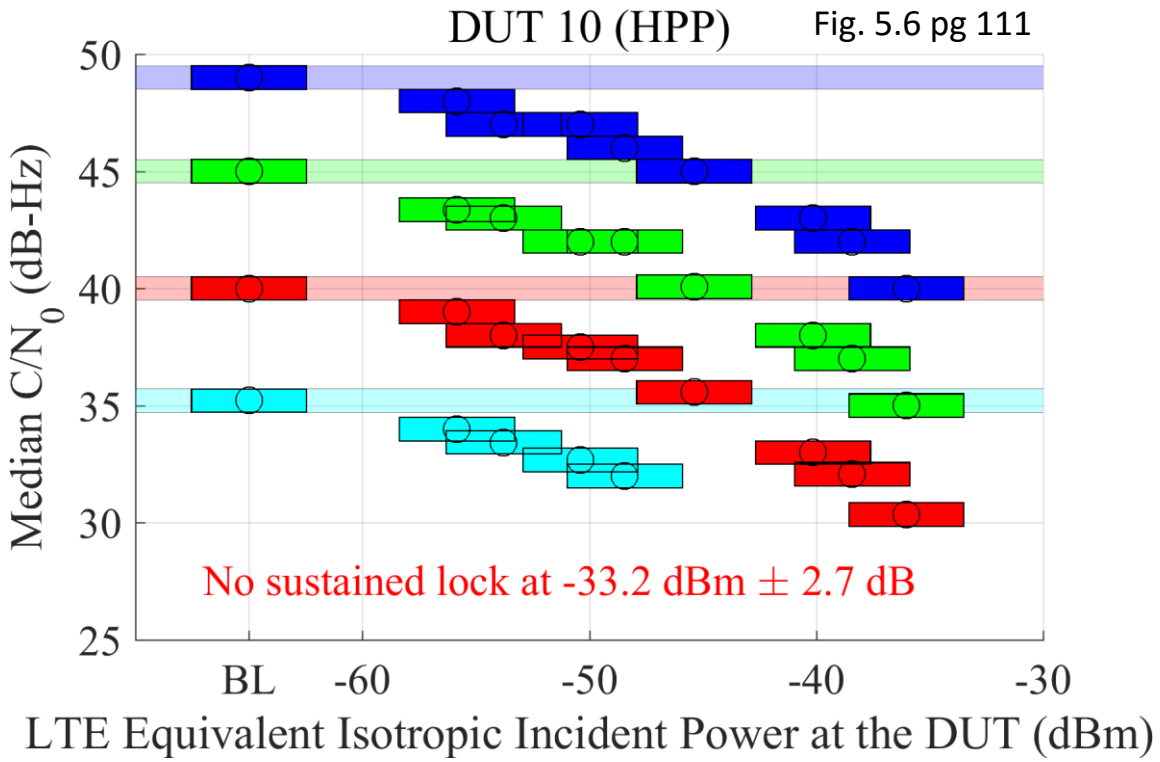


Fig. 5.6 pg 111

-128.5 dBm	Baseline (BL) – No LTE Power	-138.5 dBm	Baseline (BL) – No LTE Power
-133.5 dBm	Baseline (BL) – No LTE Power	-143.5 dBm	Baseline (BL) – No LTE Power

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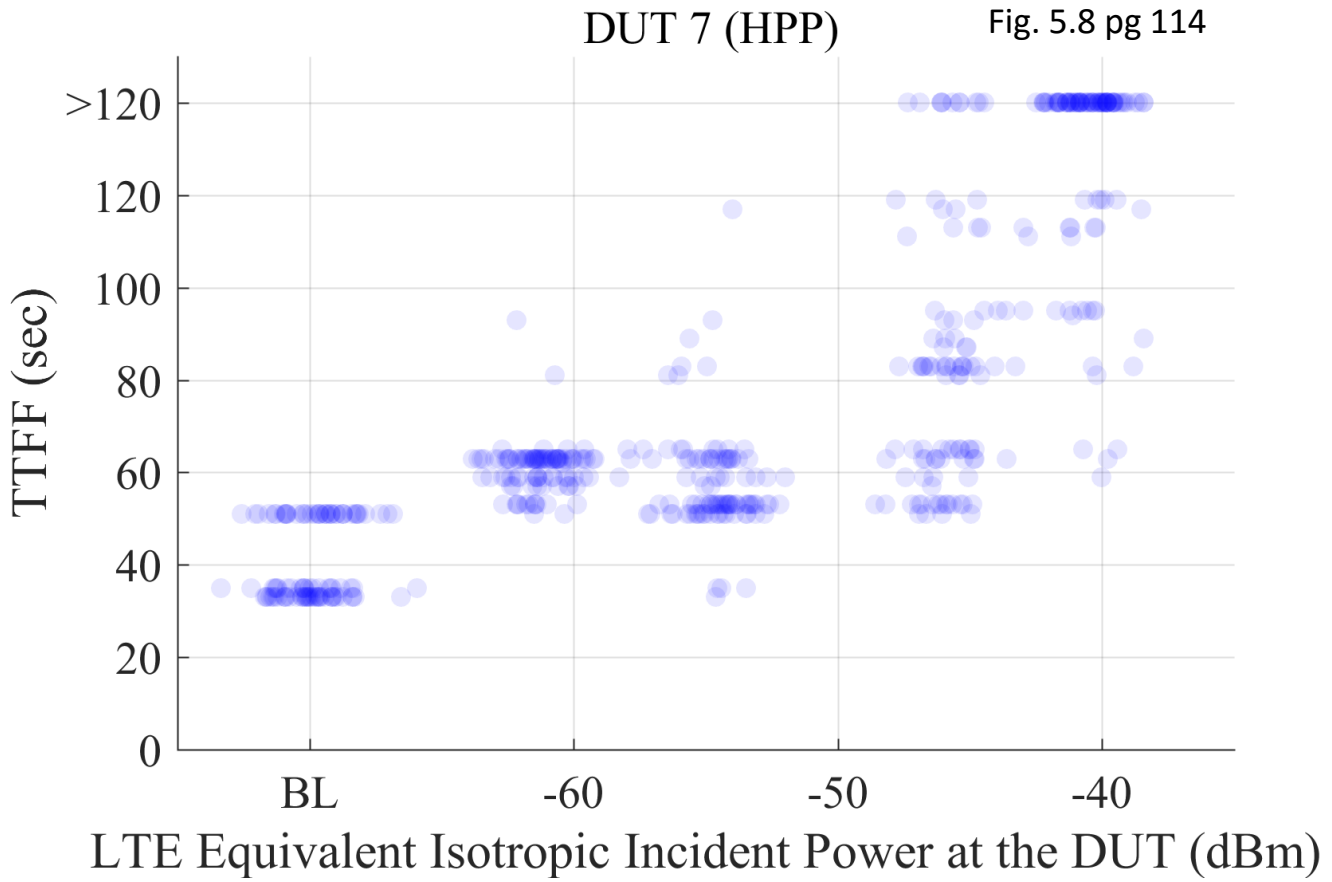
Data Analysis for TTFF & TTFR tests

Scatterplots

- Raw TTFF data
- Horizontal coordinate randomly distributed based on the estimated uncertainty for LTE EIIP

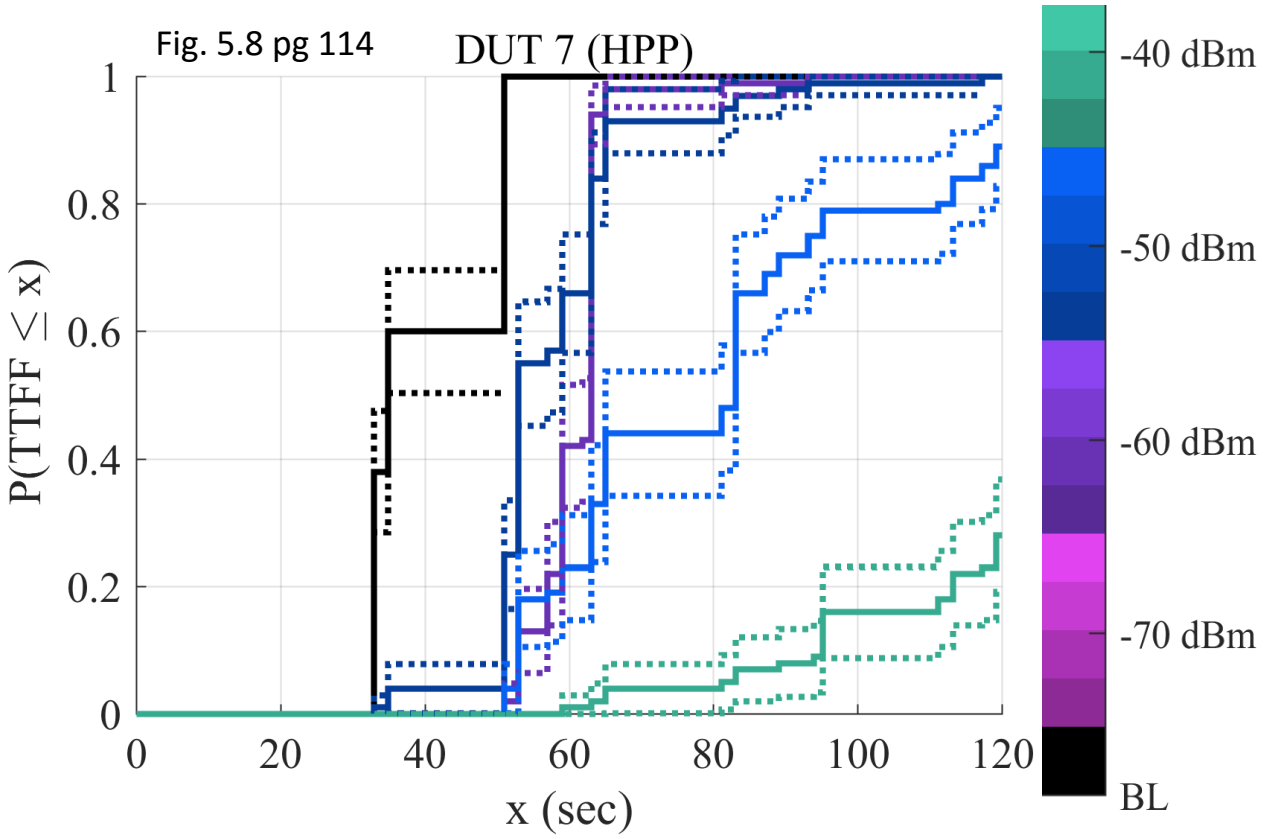
Fig. 5.8 pg 114



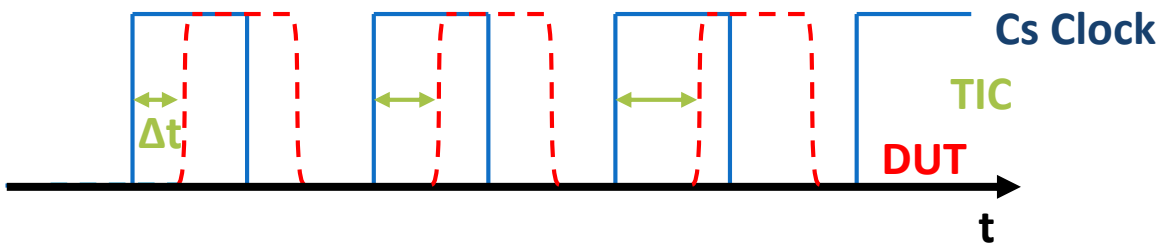
TTFF & TTFR tests

Empirical cumulative distribution function (CDF) plots

- Kaplan-Meier estimate for empirical CDF (solid lines)
- Pointwise 95% confidence bands (dashed lines)
- Colorbar used to convey LTE power level, (BL) indicates baseline

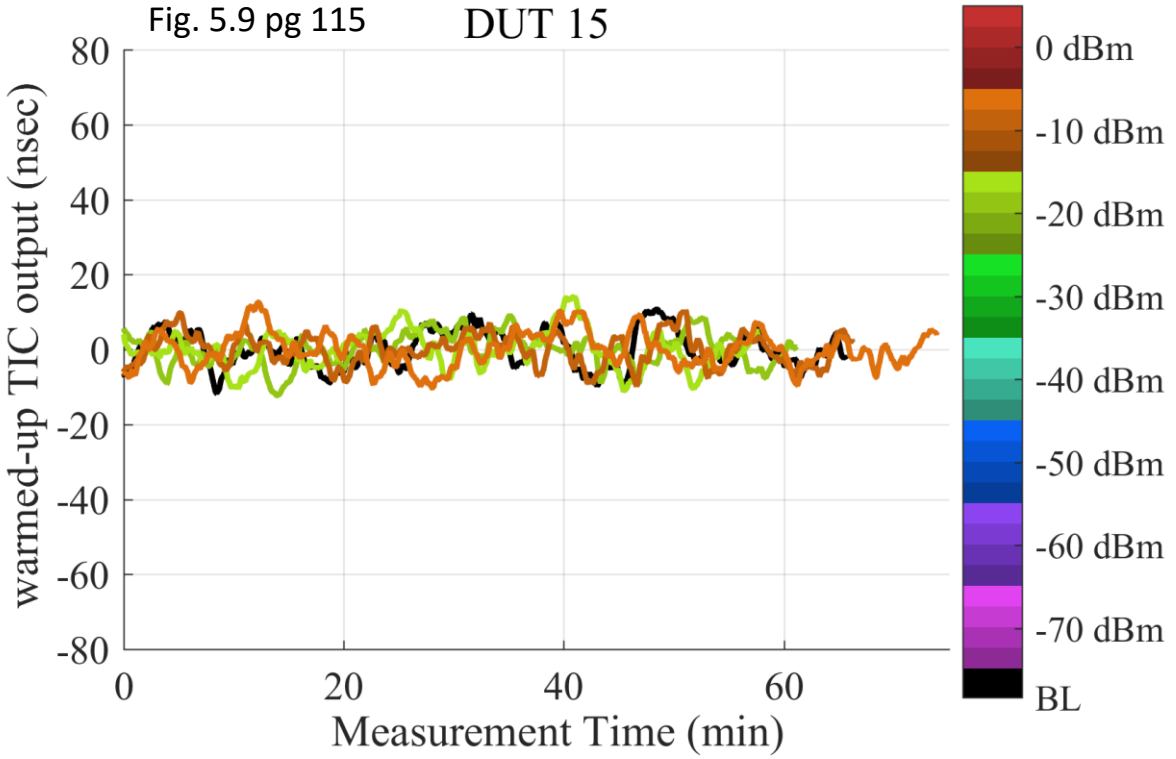


Data Analysis for Timing Tests



Time interval counter (TIC) measures the time interval between the reference cesium (Cs) Clock and the DUT.

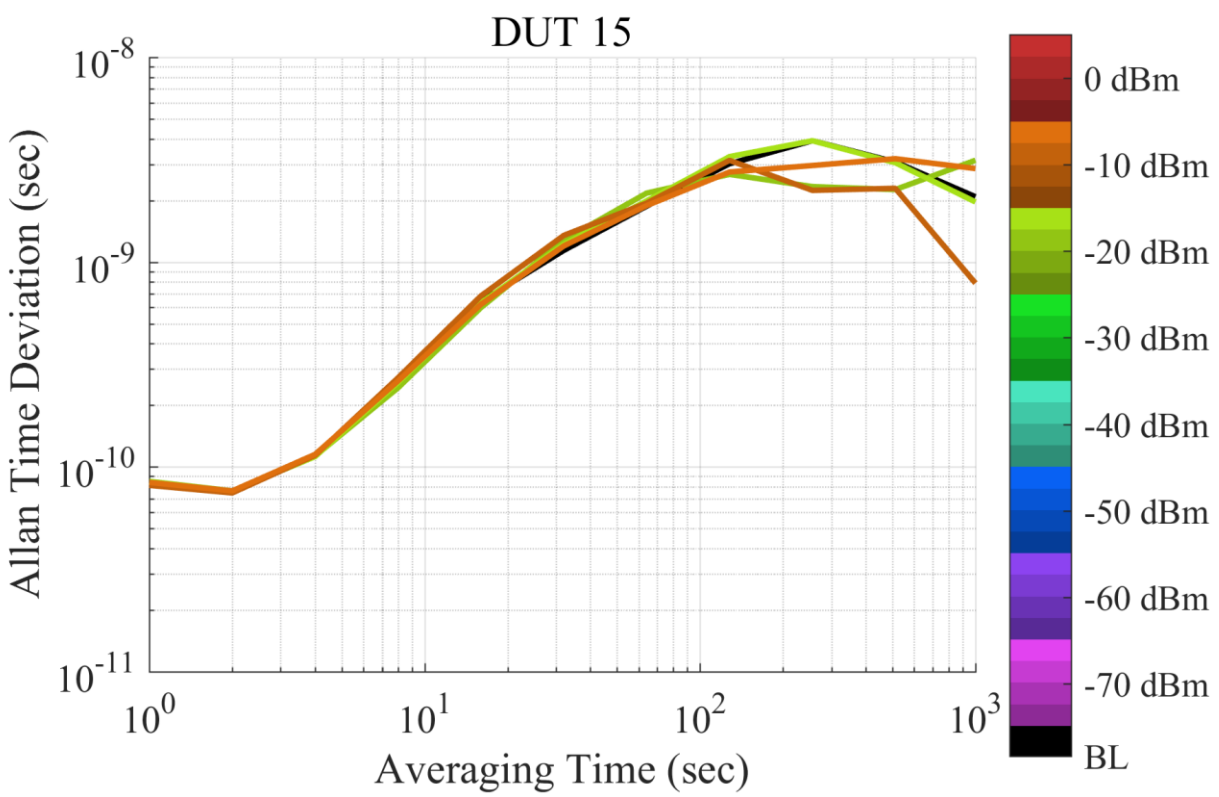
- To allow for DUT conditioning, data from first 75 min not used for analysis.
- Remaining 75 min capture adjusted by subtracting its mean.
- Resulting warmed-up TIC output was plotted and analyzed.

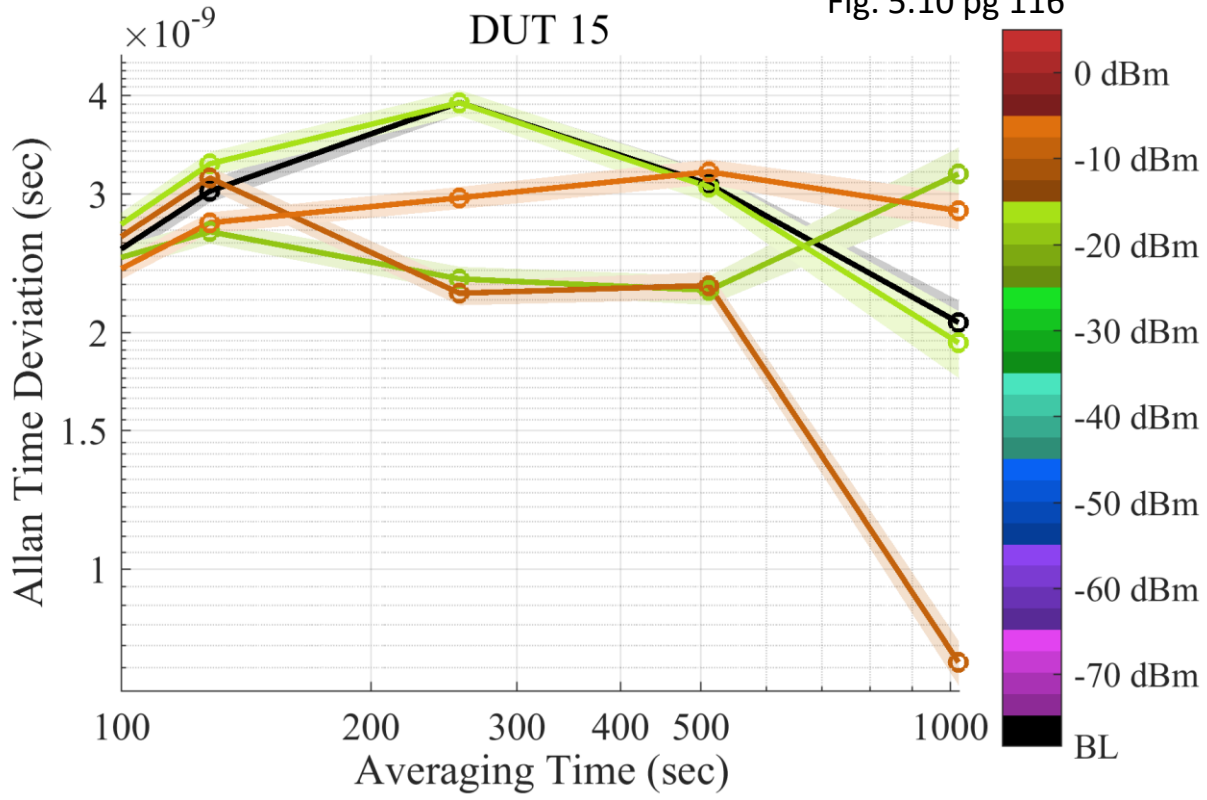


Allan Time Deviation plots

Full-scale and zoom plots with pointwise 95% confidence band

Fig. 5.10 pg 116





DUT Antenna Response

- External DUT antennas were measured
- Active antenna response is normalized

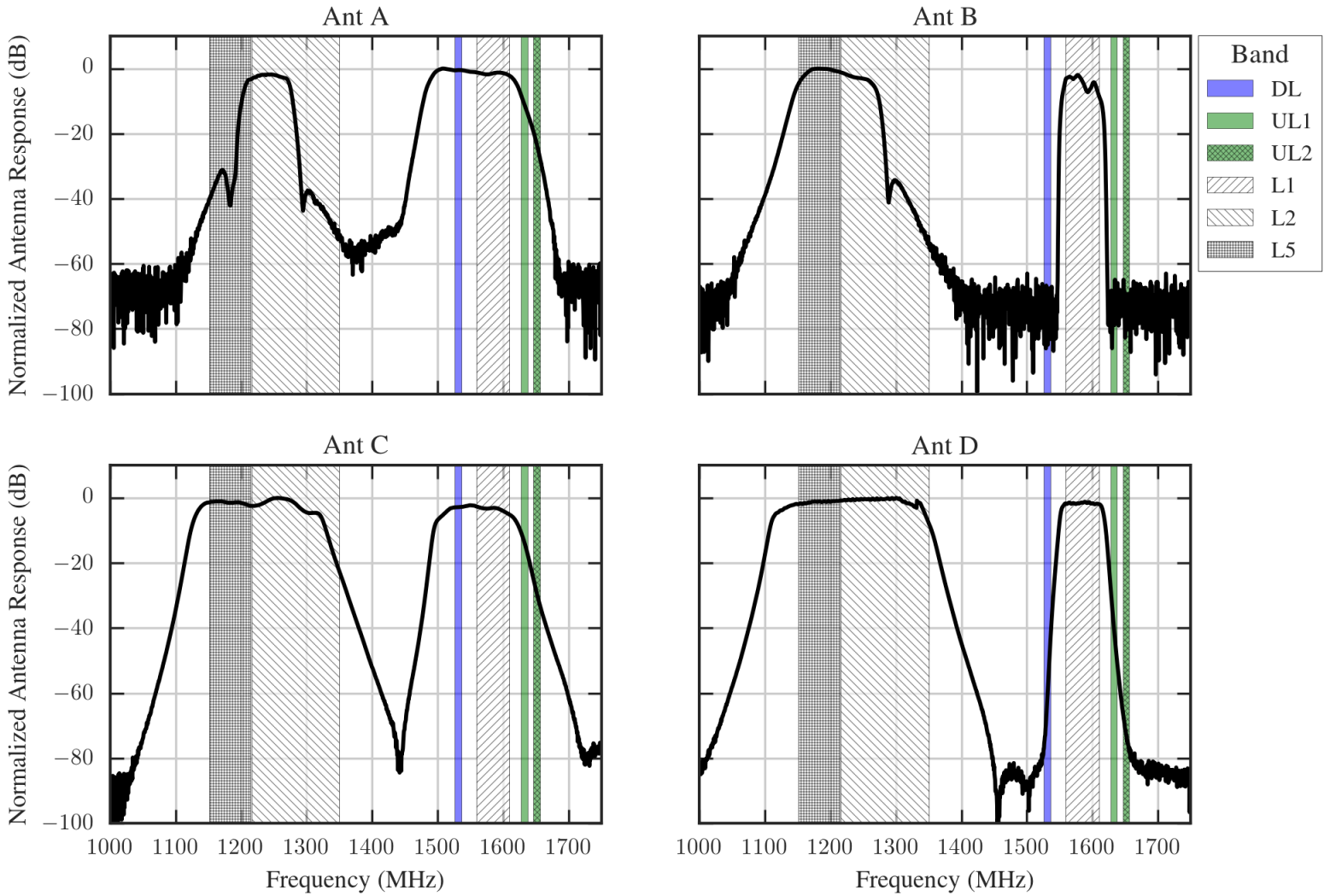


Fig. 6.2 – pg. 122

DUT Antenna Response

- External DUT antennas were measured
- Active antenna response is normalized

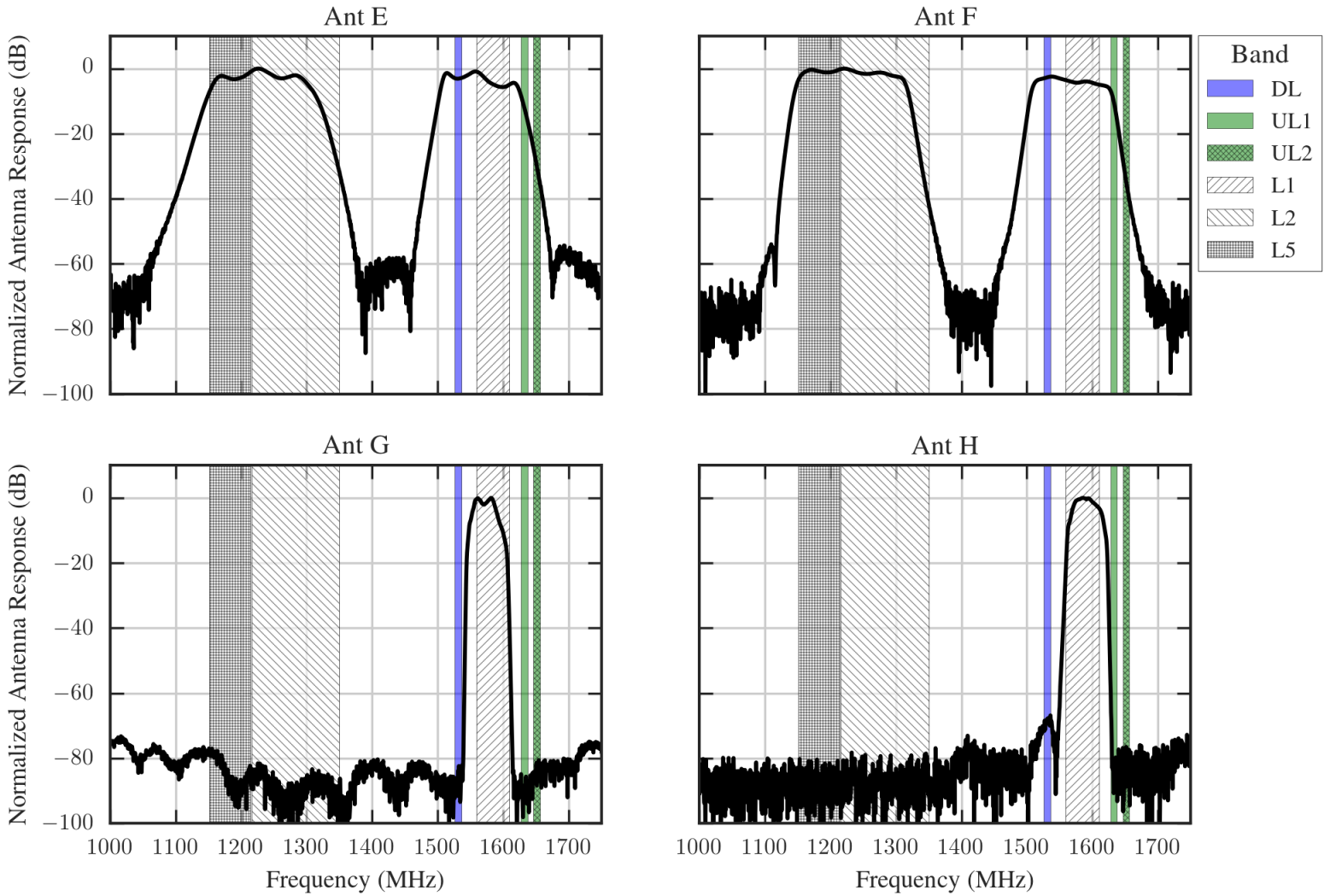


Fig. 6.3 – pg. 123

Errata for "LTE Impacts on GPS: Final Test Report"

Location	Corrected text
Page xxxviii, C.15	Missing space between "Underline" and "Indicates"
Page xxix, F.5	"97.55%" should be "97.5%"
Page 18, Fig 2.1 vs page 54 Table 3.6	Quoted RF power values found in table 3.6 supersede values reported in figure 2.1. Discrepancy is due to refined calibration corrections.
Page 98, Table 5.3	"GPGGA" incorrectly listed in both columns (should only be in "Analyzed" column). "BESTPOSA" is repeated in the "Analyzed" column.
Page 223, caption to Figure 6.99	"CDF plots of TTFF from lock acquisition reported by HPP receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is DL."
Page 224, caption to Figure 6.100	"Scatterplots of TTFF from lock acquisition reported by HPP receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is DL."
Page 225, caption to Figure 6.101	"CDF plots of TTFF from lock acquisition reported by RTK receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is UL1."
Page 226, caption to Figure 6.102	"Scatterplots of TTFF from lock acquisition reported by RTK receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is UL1."
Page 227, caption to Figure 6.103	"CDF plots of TTFR from lock acquisition reported by GLN receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is UL1."
Page 228, caption to Figure 6.104	"Scatterplots of TTFR from lock acquisition reported by GLN receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is UL1."
Page 229, caption to Figure 6.105	"CDF plots of TTFF from lock acquisition reported by HPP receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is UL1.
Page 230, caption to Figure 6.106	"Scatterplots of TTFF from lock acquisition reported by HPP receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is UL1."
Page 231, caption to Figure 6.107	"CDF plots of TTFF from lock acquisition reported by RTK receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is DL."
Page 232, caption to Figure 6.108	"Scatterplots of TTFF from lock acquisition reported by RTK receivers at different LTE power levels. The GPS scenario is TTFF, and the type of incident LTE is DL."

Presentation of Results

Nominal Satellite Conditions

Limited Satellite Conditions

TTFF & TTFR

Timing Tests

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General Location and Navigation

Nominal Satellite Constellation

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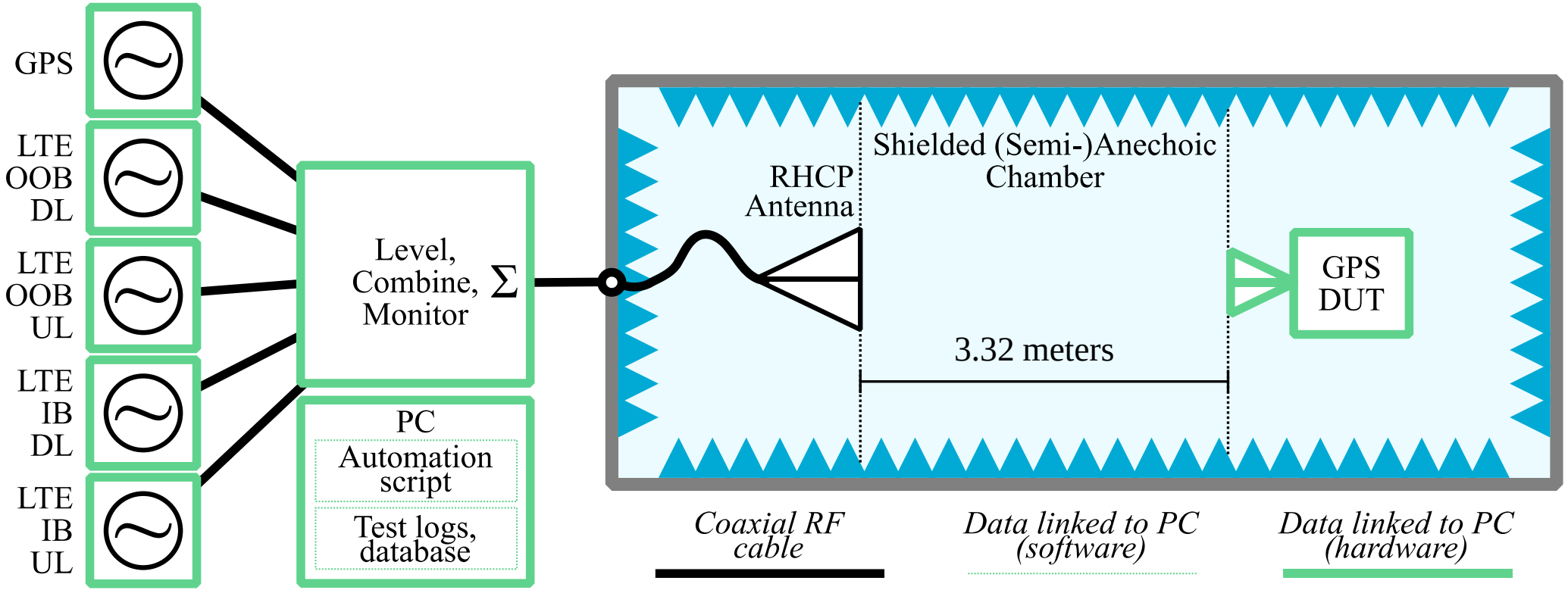
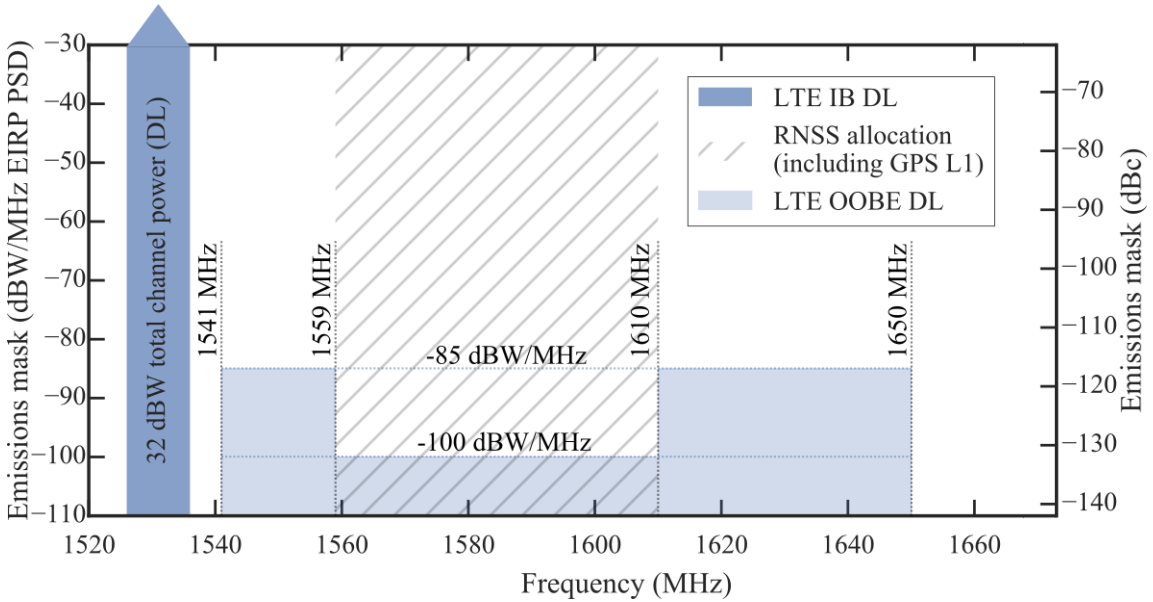
GLN Setup


GPS
LTE OOB DL
LTE OOB UL
LTE IB DL
LTE IB UL
Level, Combine, Monitor
Σ
PC
Automation script
Test logs, database
RHCP Antenna
Shielded (Semi-)Anechoic Chamber
GPS DUT
3.32 meters
Coaxial RF cable
Data linked to PC (software)
Data linked to PC (hardware)

General Location and Navigation

- Nominal Satellite Condition
  - **Downlink**
  - Uplink 1
  - Uplink 2
  - Combo DL + UL1



General Location

- C/N0 scatter plots
- Downlink
- Nominal satellite condition
- 600 points per LTE power level per satellite

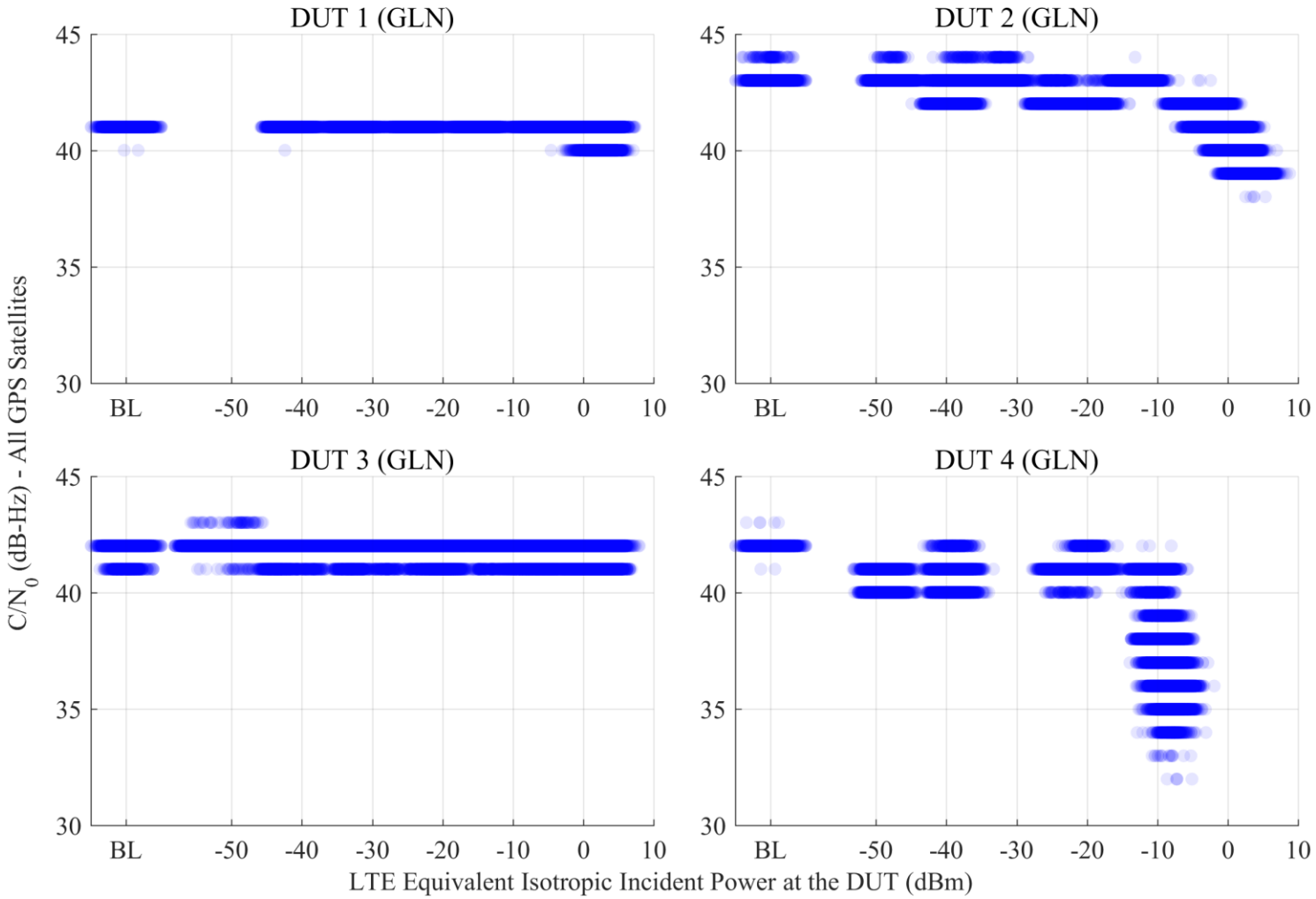


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Fig. 6.4 – pg. 125

General Location

- 3D position error scatter plots
- Downlink
- Nominal satellite condition

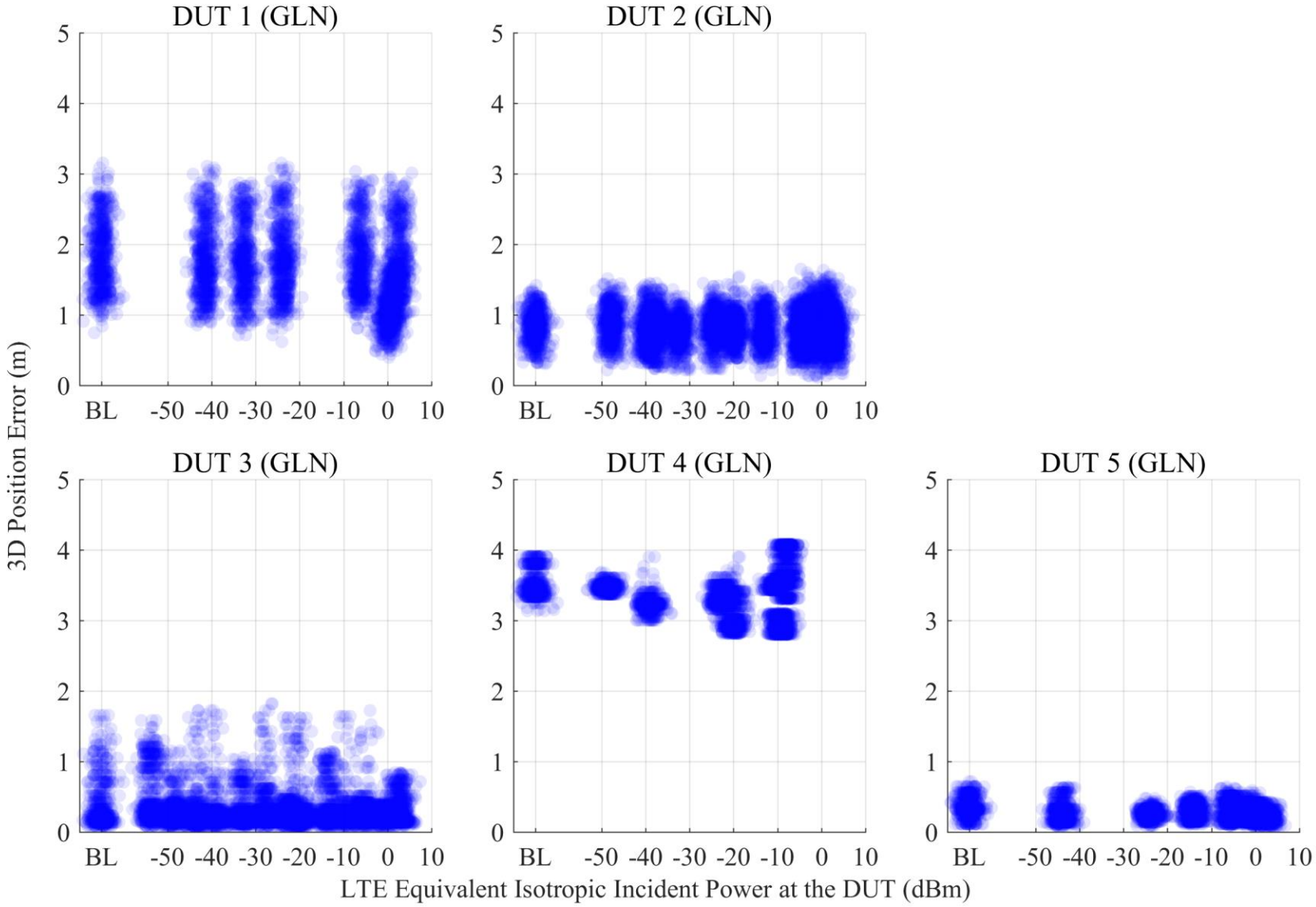

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Fig. 6.6 – pg. 127

General Location

- 95% confidence regions for median C/N_0
- Downlink
- Nominal satellite condition

Baseline (BL) – No LTE Power

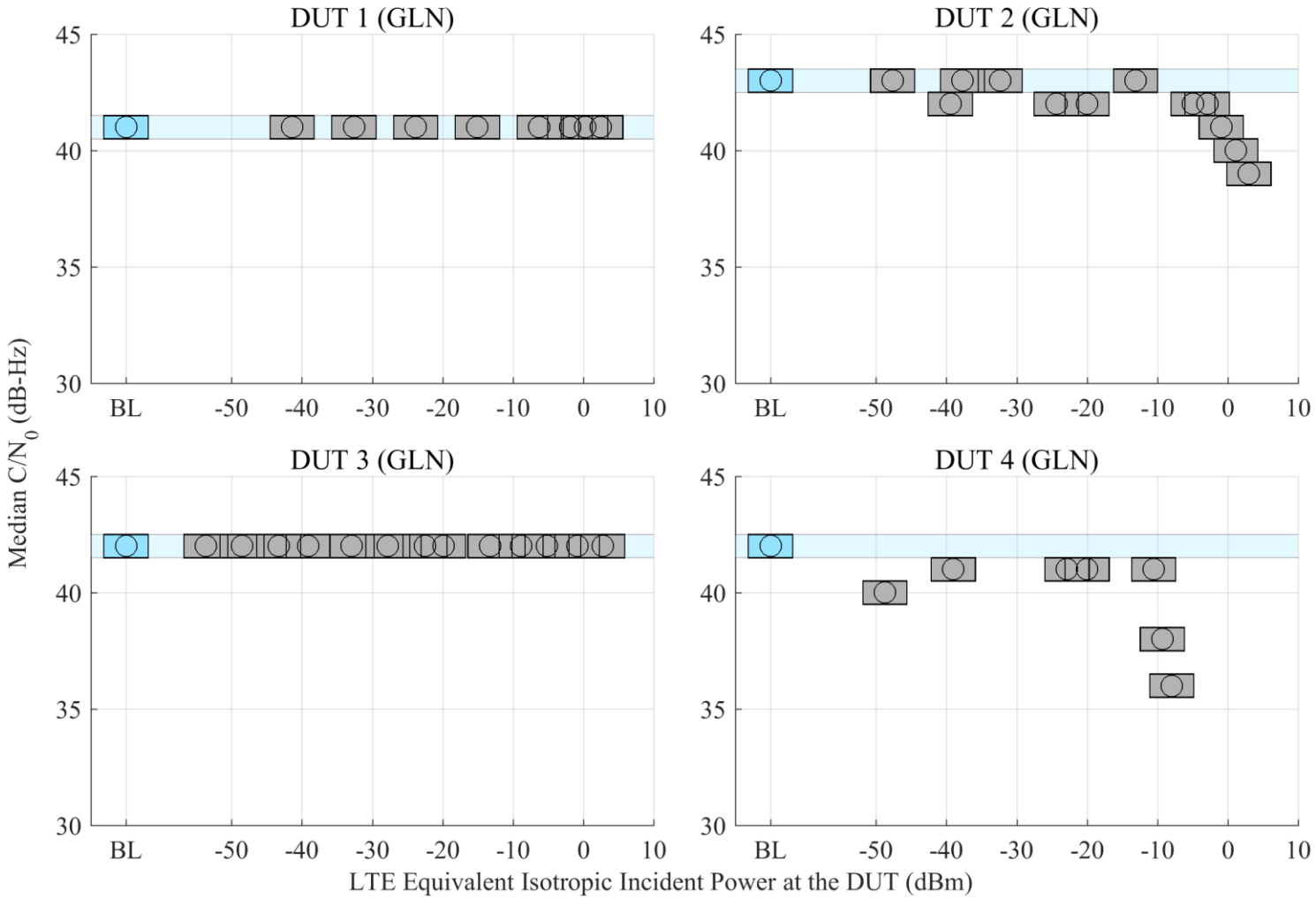

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Fig. 6.5 – pg. 126

General Location

- 95% confidence regions for median 3D position error
- Downlink
- Nominal satellite condition

Baseline (BL) – No LTE Power

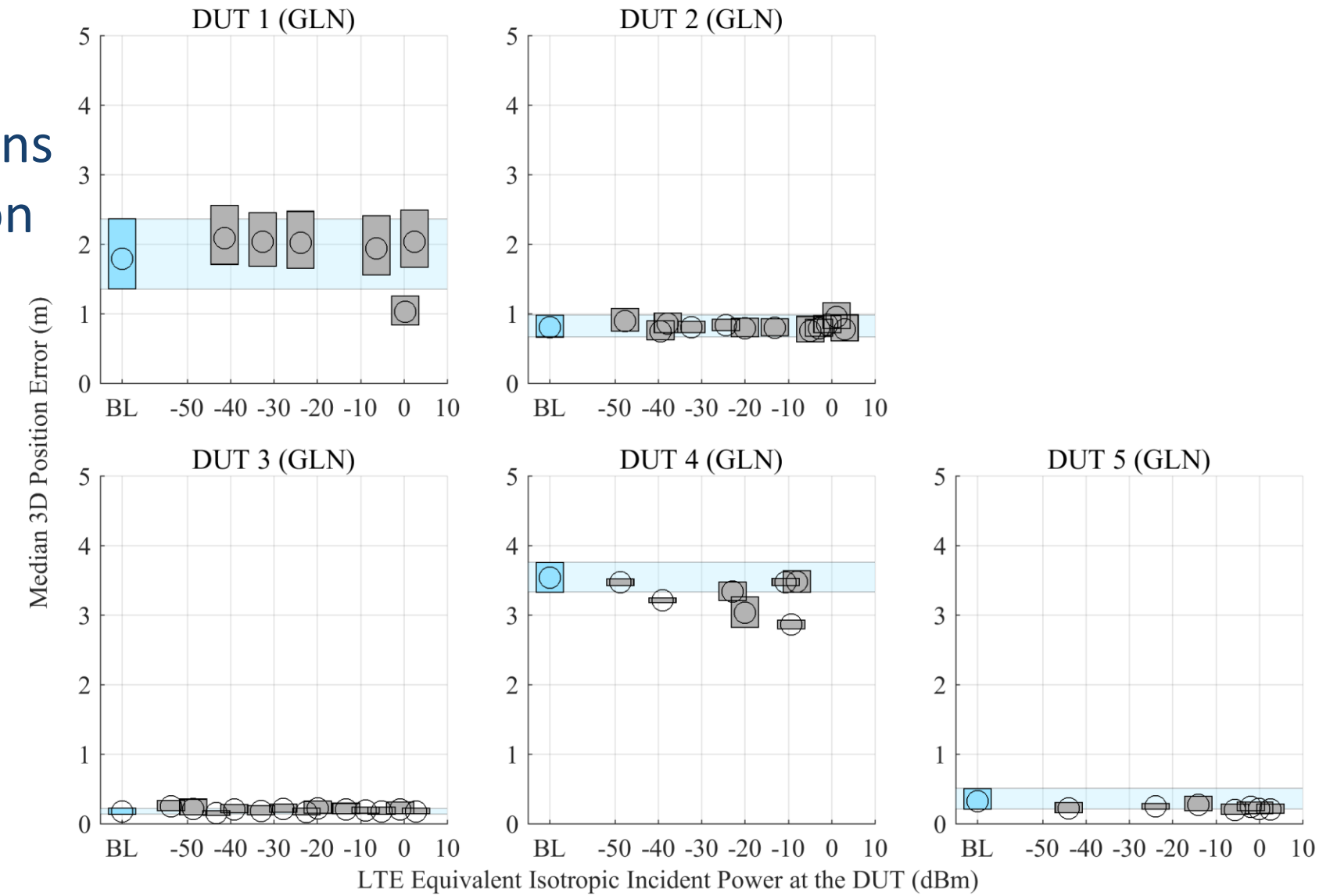

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Fig. 6.7 – pg. 128

General Location

- Number of reported satellites in view scatter plot
- Downlink
- Nominal satellite condition

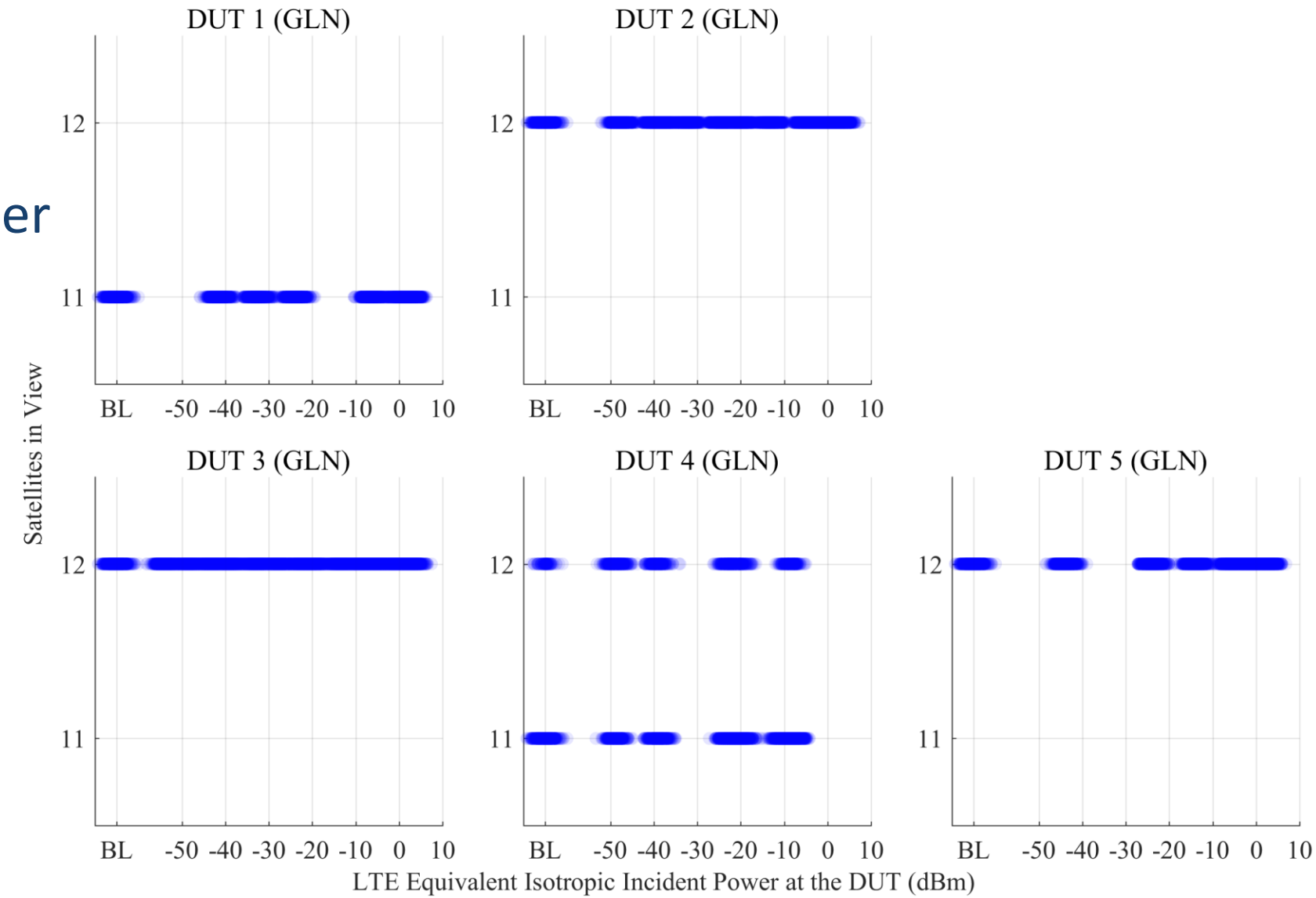

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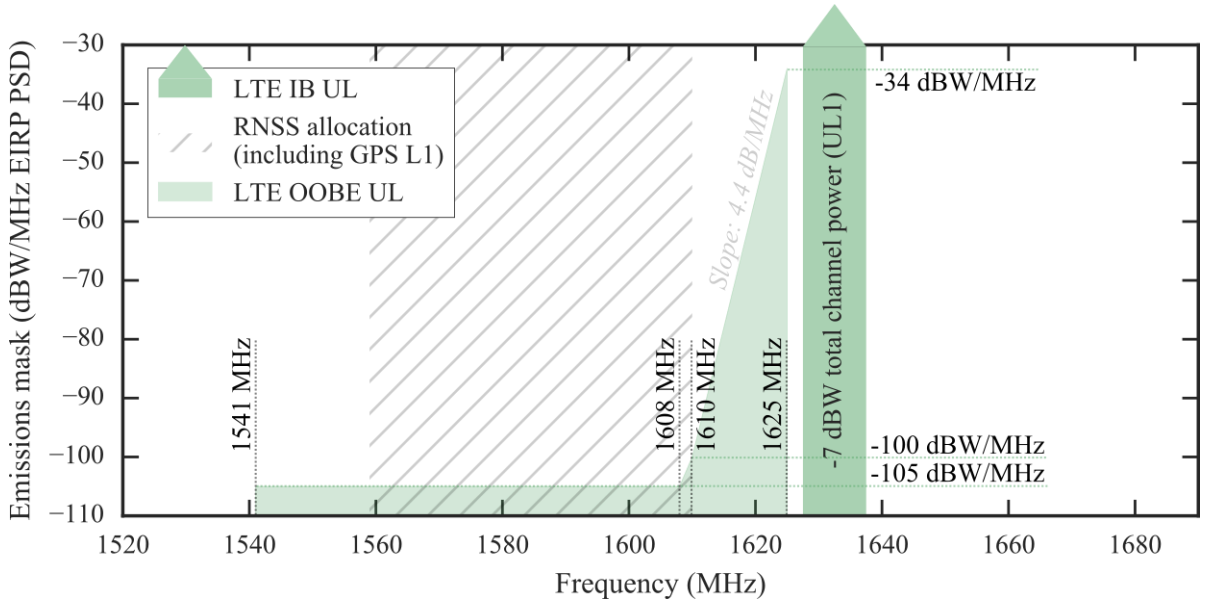
Fig. 6.8 – pg. 129

General Location and Navigation

- Nominal Satellite Condition
  - Downlink
  - **Uplink 1**
  - Uplink 2
  - Combo DL + UL1



General Location

- C/N0 scatter plots
- Uplink 1
- Nominal satellite condition
- 600 points per LTE power level per satellite

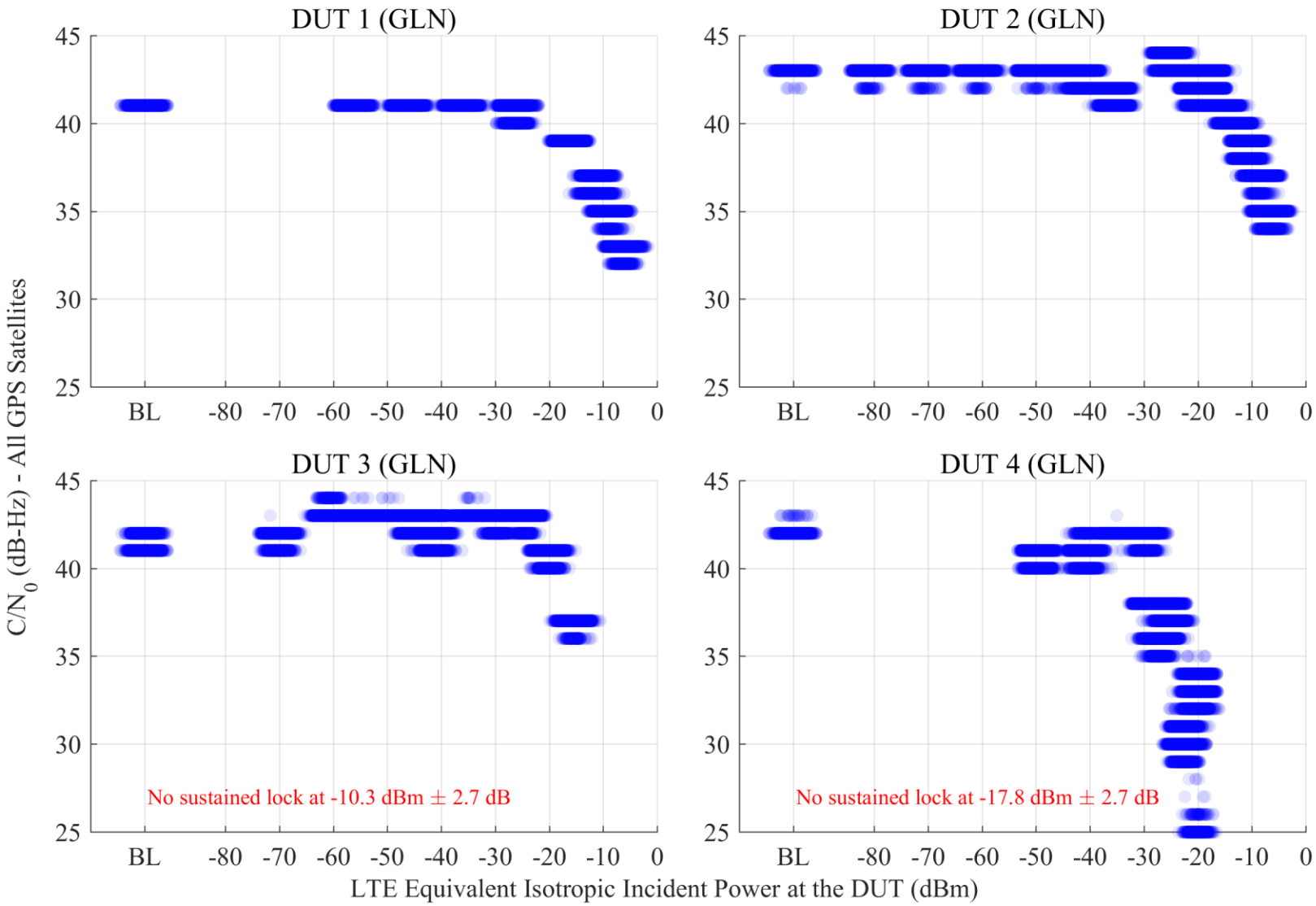


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Fig. 6.9 – pg. 130

General Location

- 3D position error scatter plots
- Uplink 1
- Nominal satellite condition

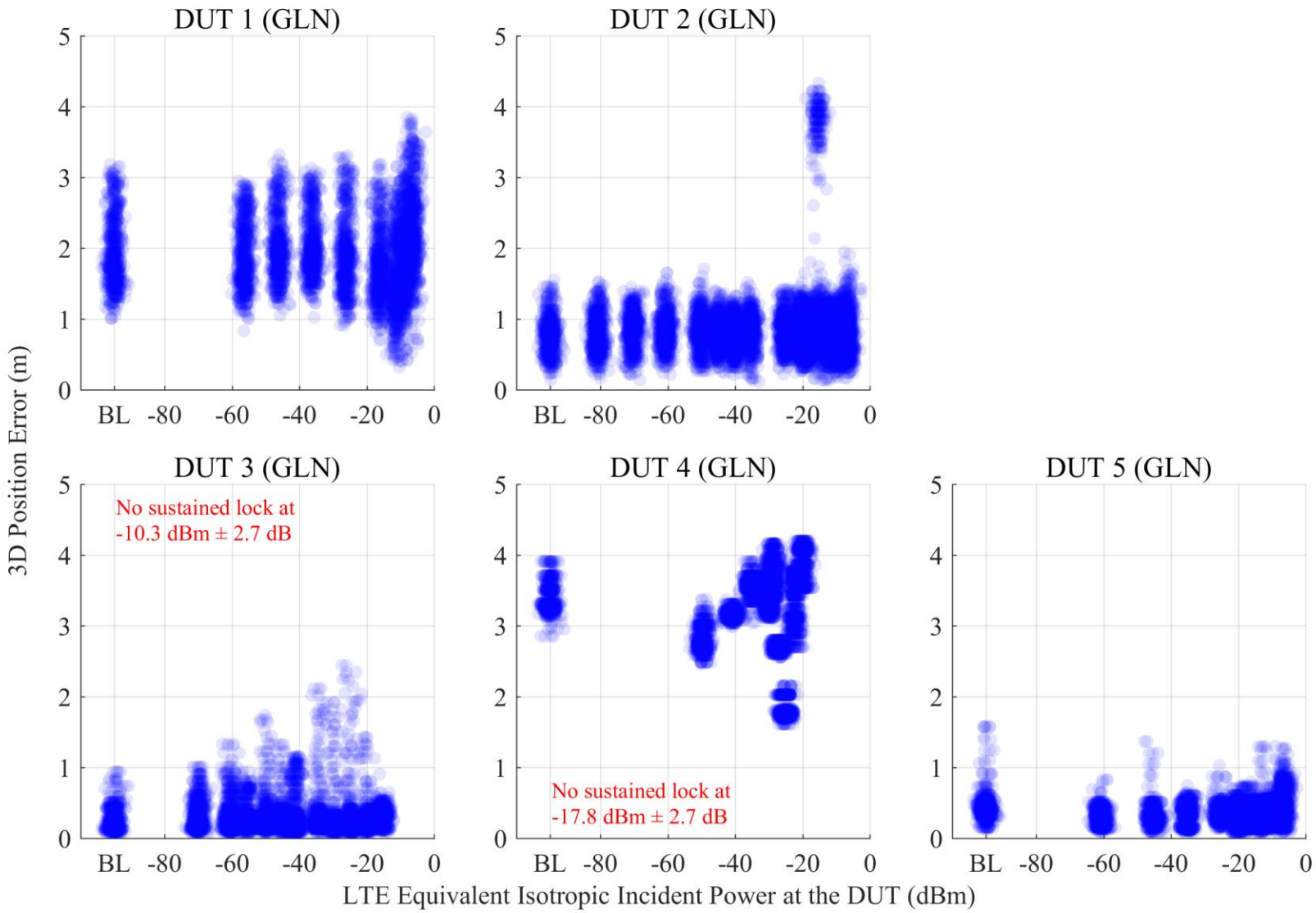

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Fig. 6.11 – pg. 132

General Location

- 95% confidence regions for median C/N_0
- Uplink 1
- Nominal satellite condition

Baseline (BL) – No LTE Power

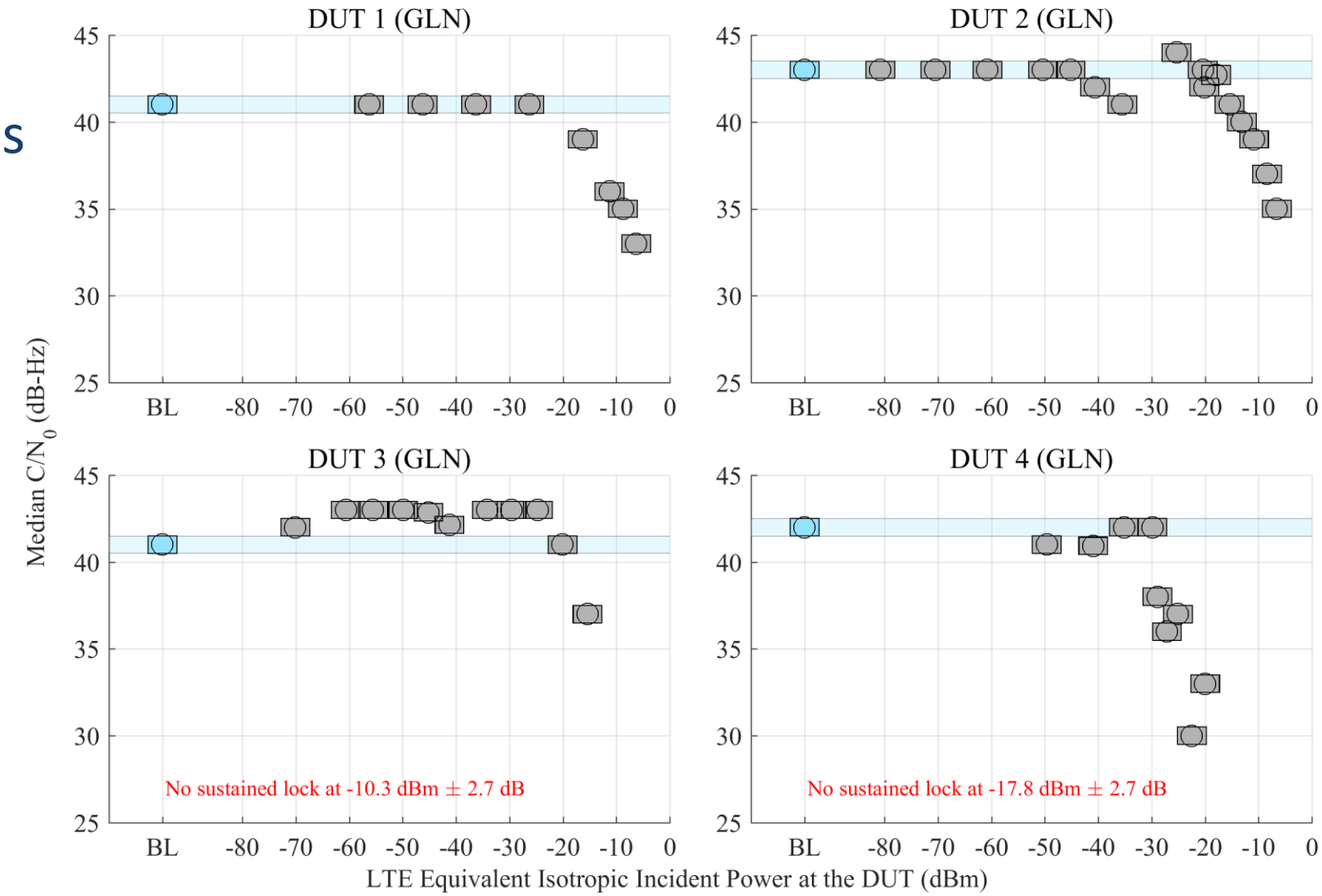

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Fig. 6.10 – pg. 131

General Location

- 95% confidence regions for median 3D position error
- Uplink 1
- Nominal satellite condition

Baseline (BL) – No LTE Power

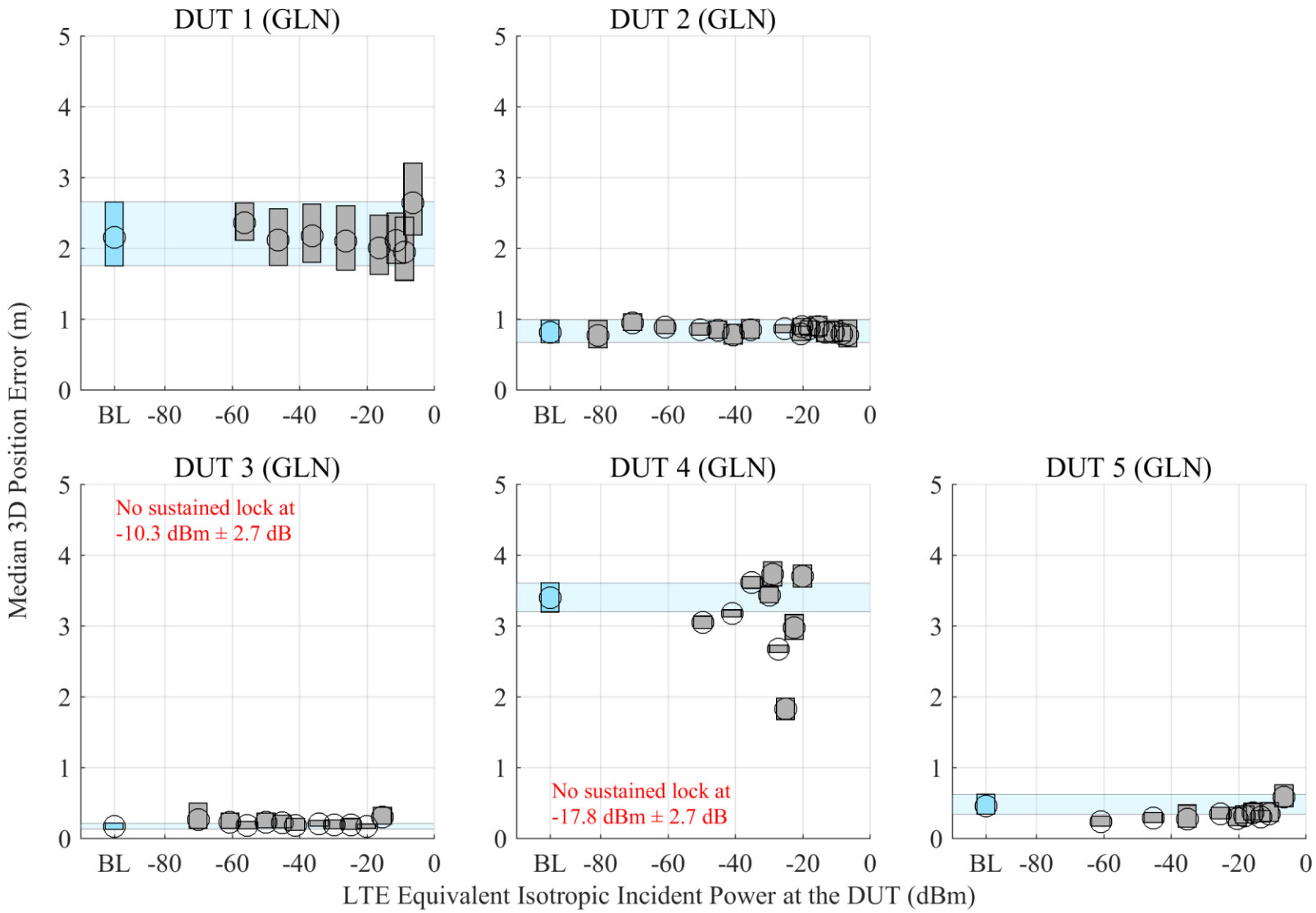

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Fig. 6.12 – pg. 133

General Location

- Number of reported satellites in view scatter plot
- Uplink 1
- Nominal satellite condition

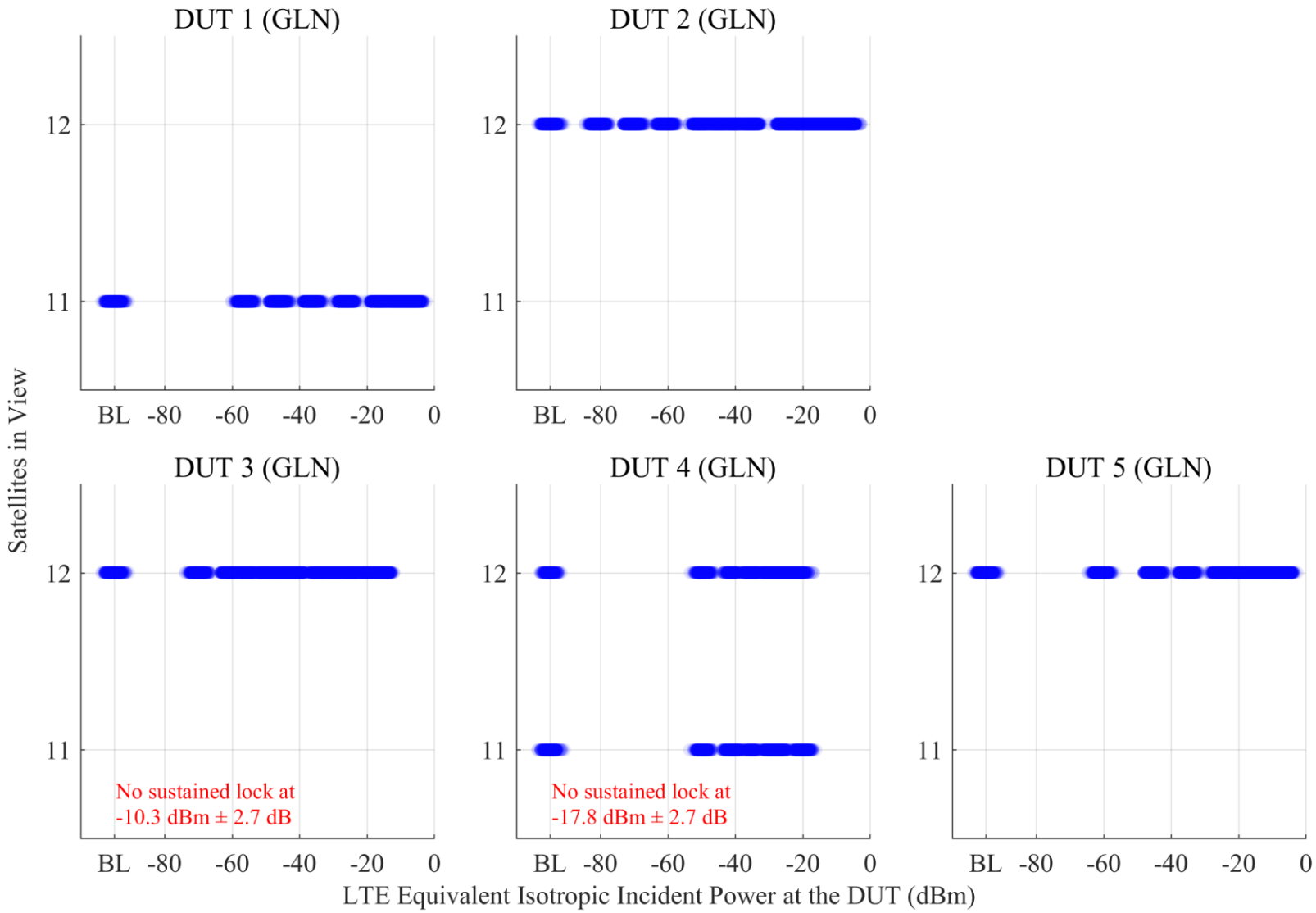

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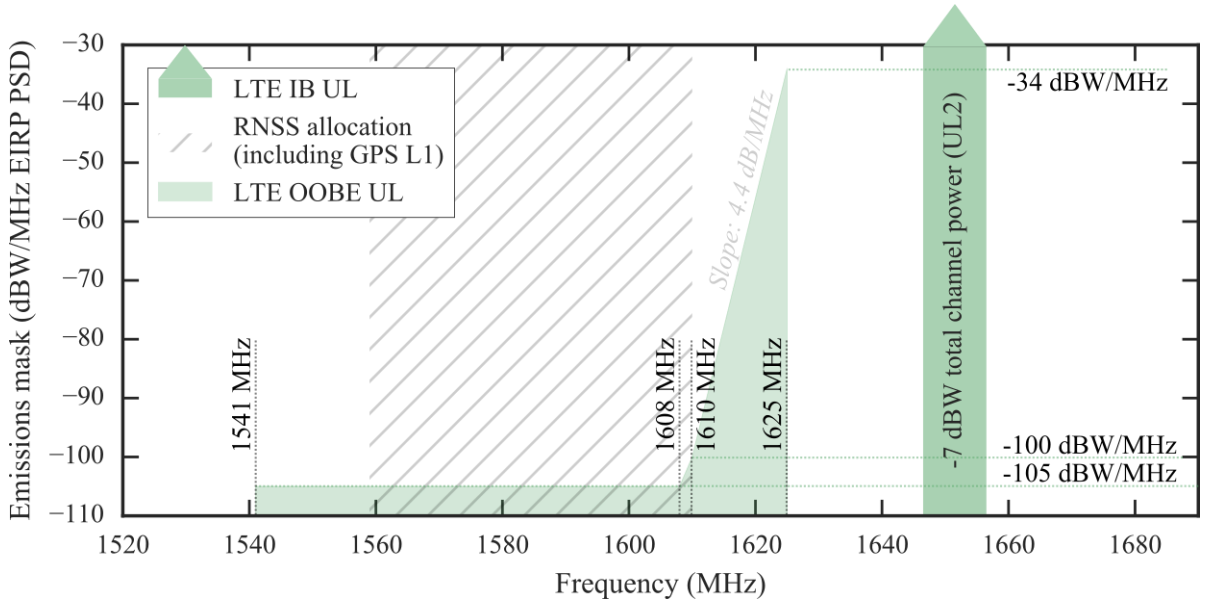
Fig. 6.13 – pg. 134

General Location and Navigation

- Nominal Satellite Condition
  - Downlink
  - Uplink 1
  - **Uplink 2**
  - Combo DL + UL1



General Location

- C/N0 scatter plots
- Uplink 2
- Nominal satellite condition
- 600 points per LTE power level per satellite

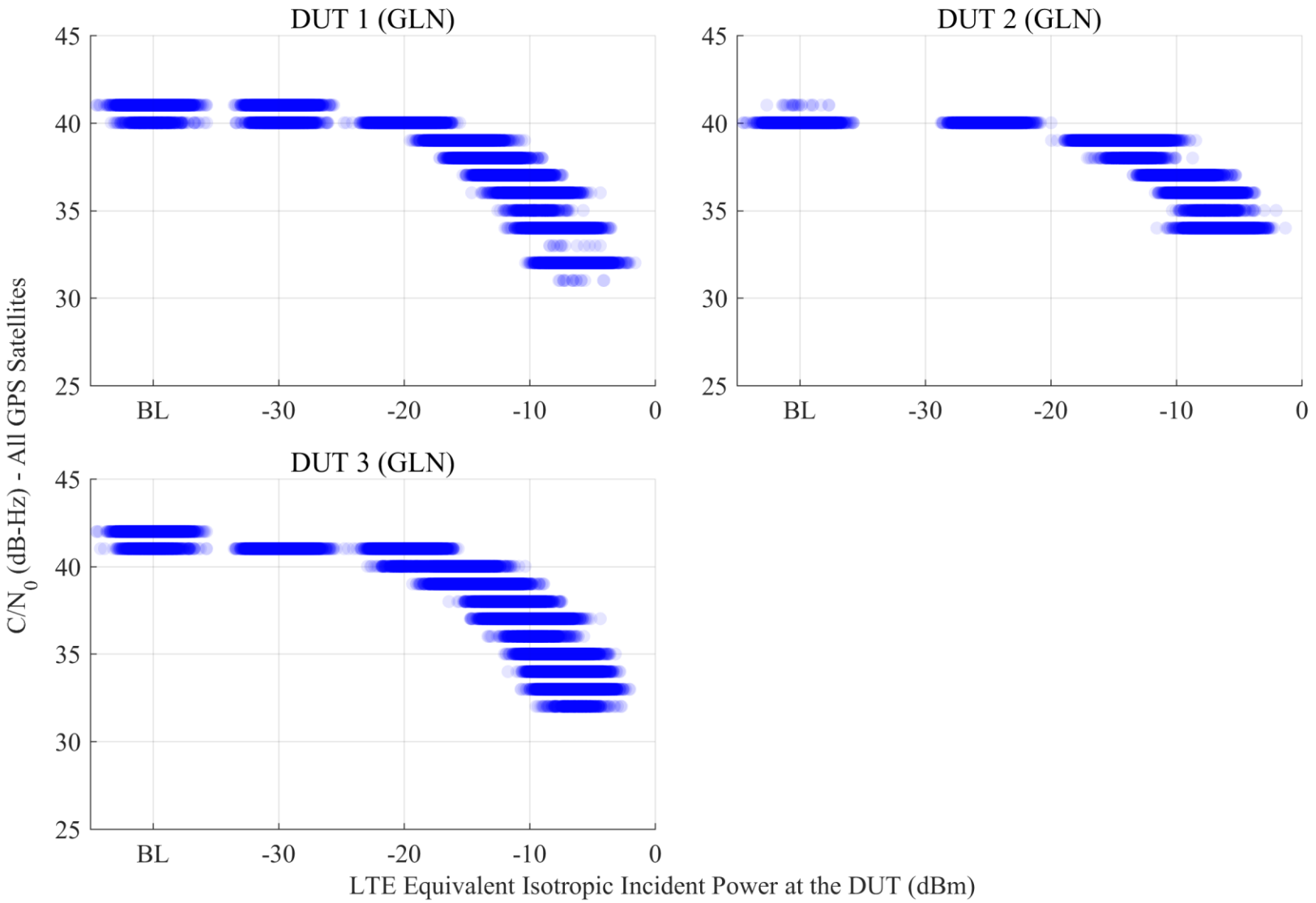


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Fig. 6.14 – pg. 135

General Location

- 3D position error scatter plots
- Uplink 2
- Nominal satellite condition

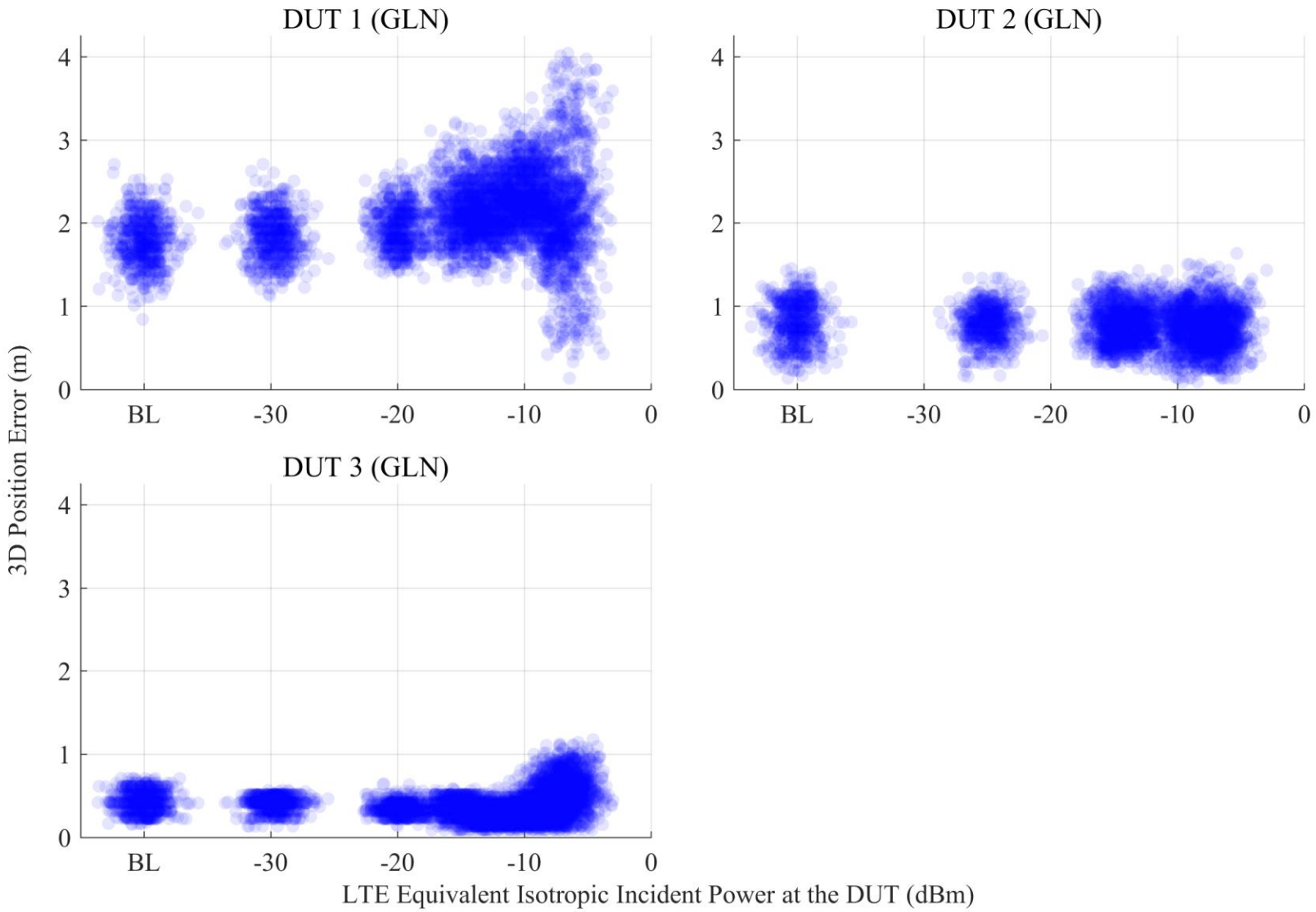

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Fig. 6.16 – pg. 137

General Location

- 95% confidence regions for median C/N_0
- Uplink 2
- Nominal satellite condition

Baseline (BL) – No LTE Power

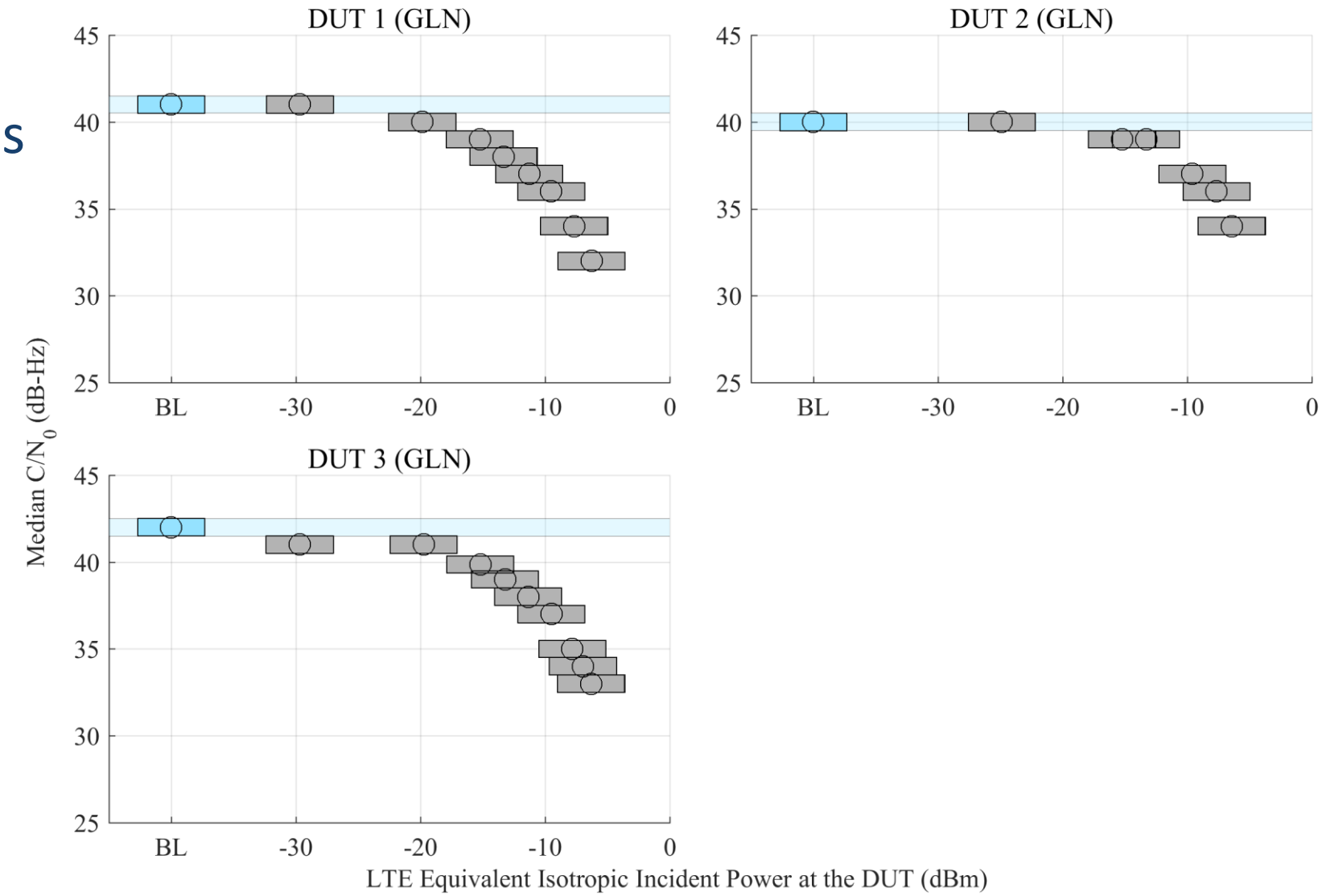

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Fig. 6.15 – pg. 136

General Location

- 95% confidence regions for median 3D position error
- Uplink 2
- Nominal satellite condition

Baseline (BL) – No LTE Power

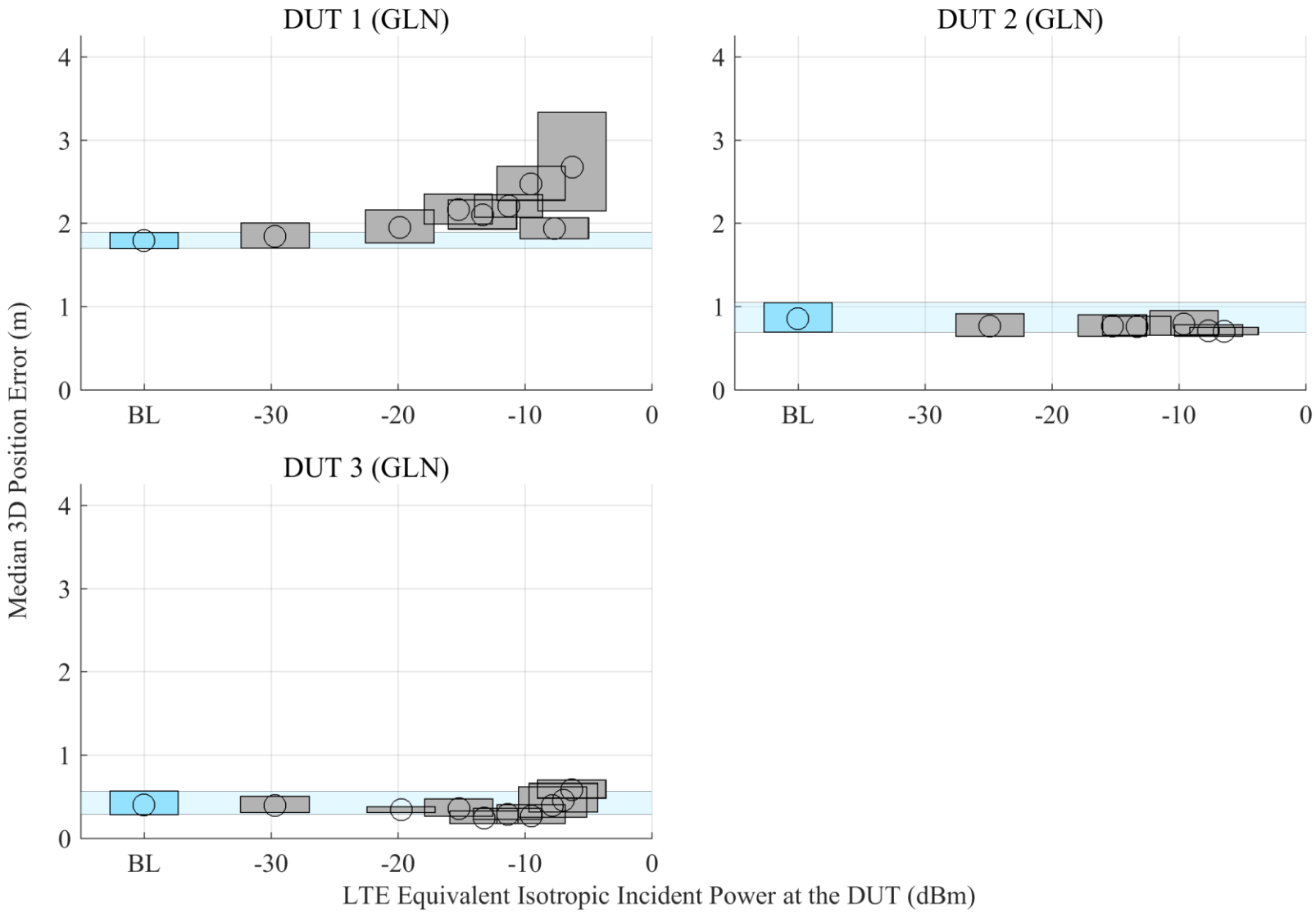

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Fig. 6.17 – pg. 138

General Location

- Number of reported satellites in view scatter plot
- Uplink 2
- Nominal satellite condition

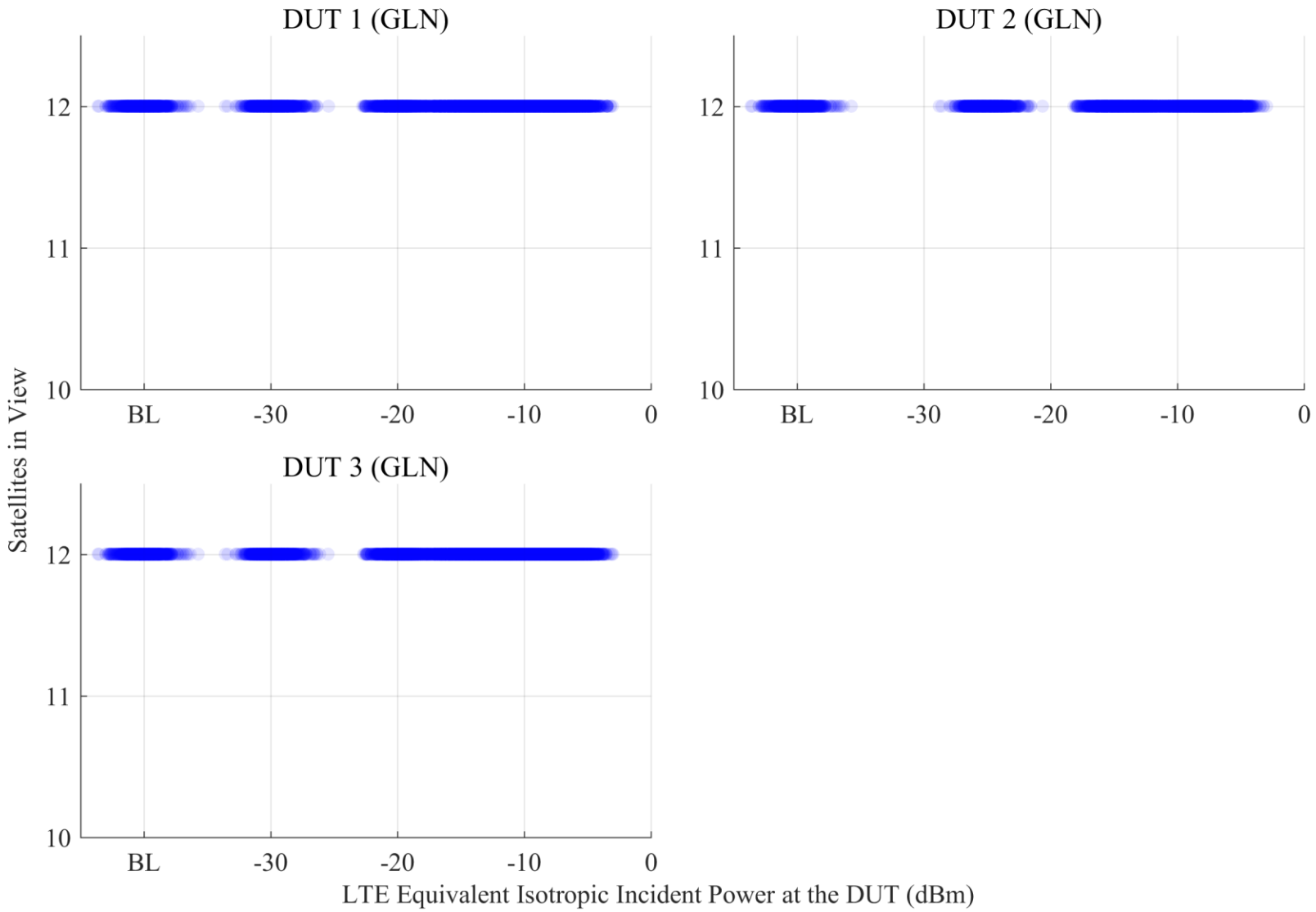

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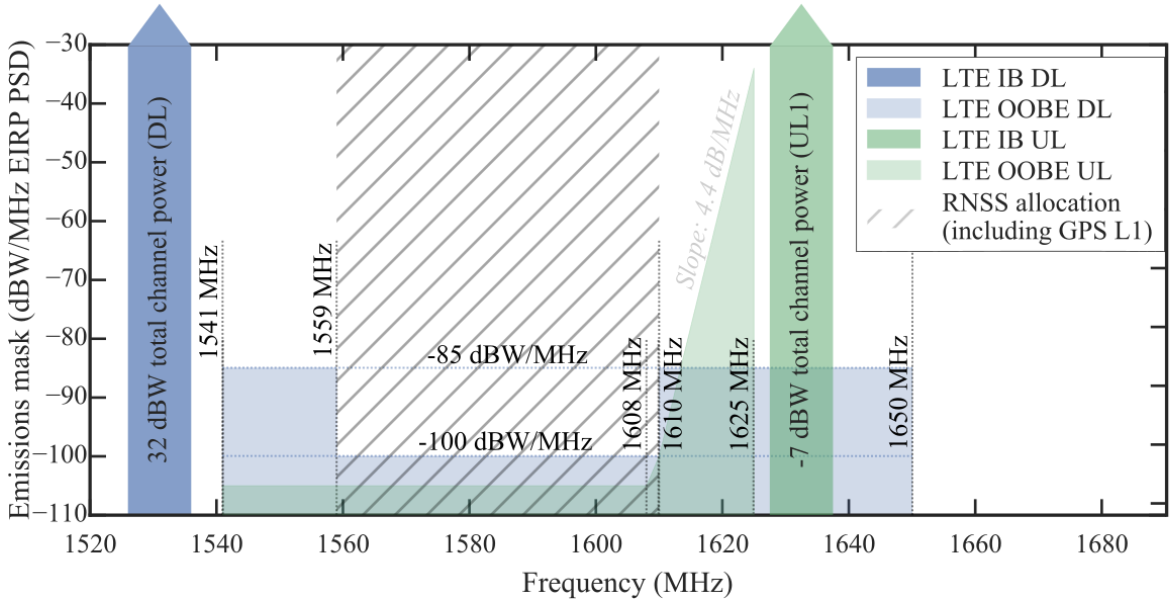
Fig. 6.18 – pg. 139

General Location and Navigation

- Nominal Satellite Condition
  - Downlink
  - Uplink 1
  - Uplink 2
  - **Combo DL + UL1**



General Location

- C/N0 scatter plots
- Combo DL + UL1
- Nominal satellite condition
- 600 points per LTE power level per satellite
- DL fixed: -50 dBm

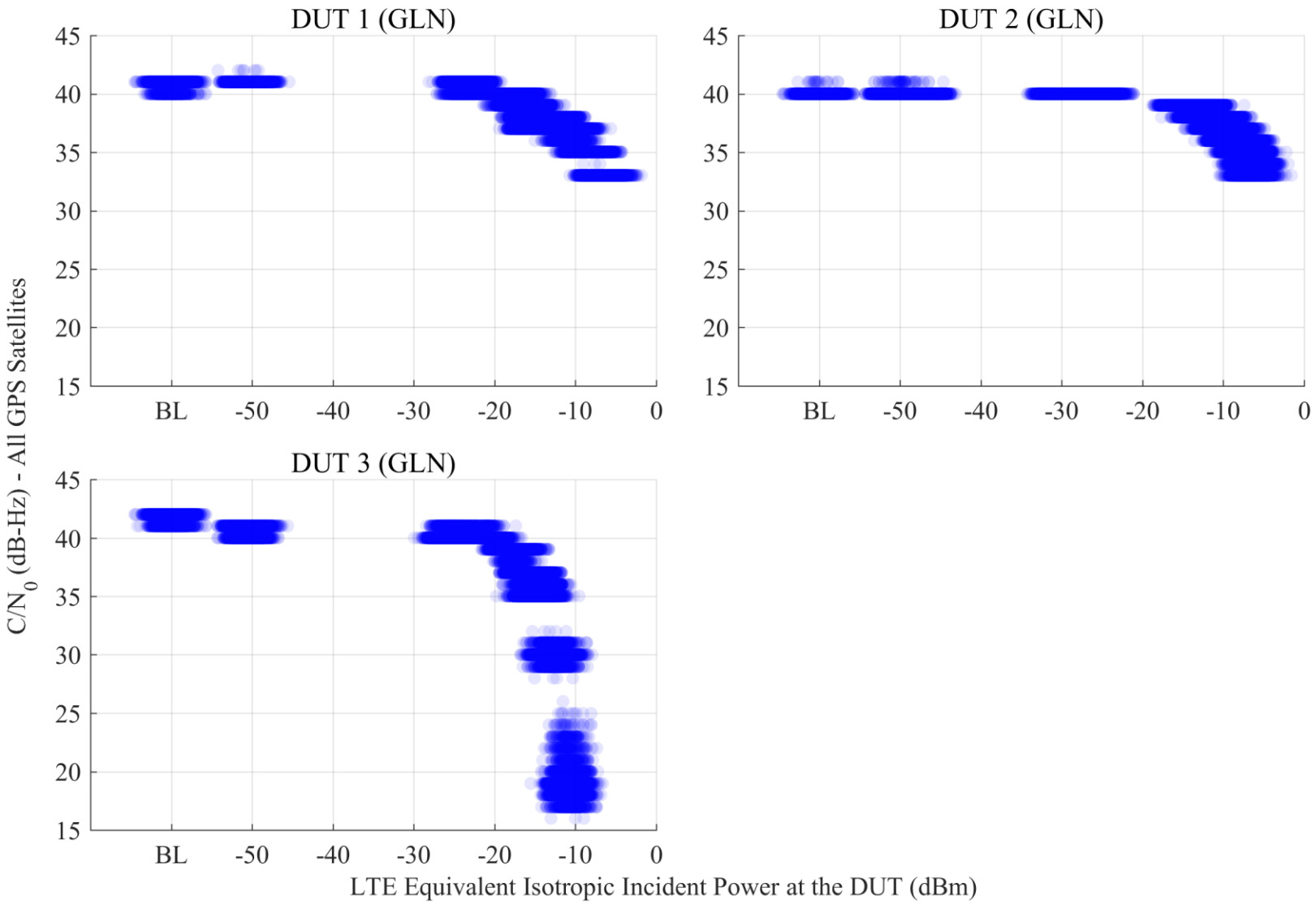


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Fig. 6.19 – pg. 140

General Location

- 3D position error scatter plots
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm

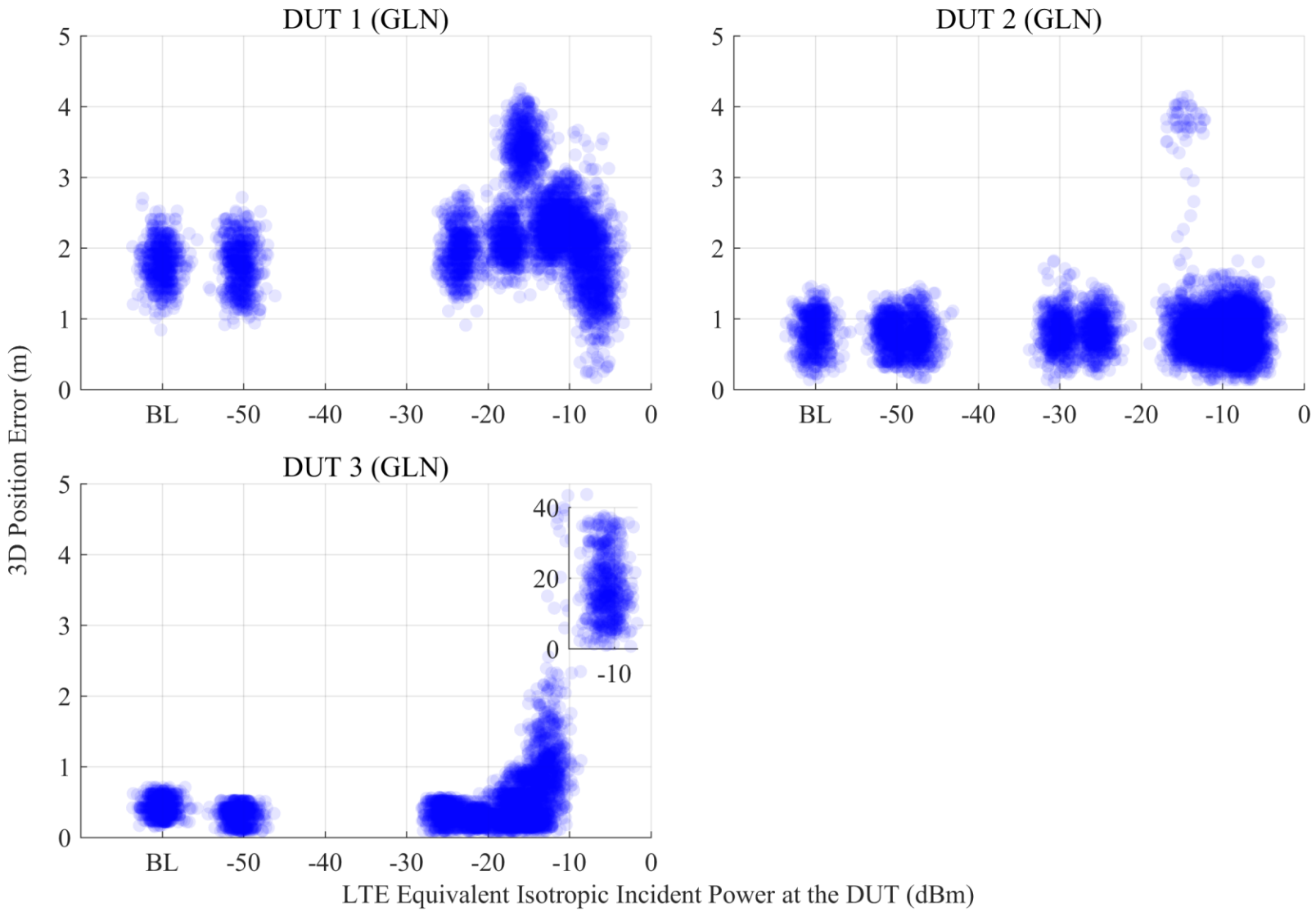

Fig. 6.21 – pg. 142

General Location

- 95% confidence regions for median C/N_0
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm

Baseline (BL) – No LTE Power

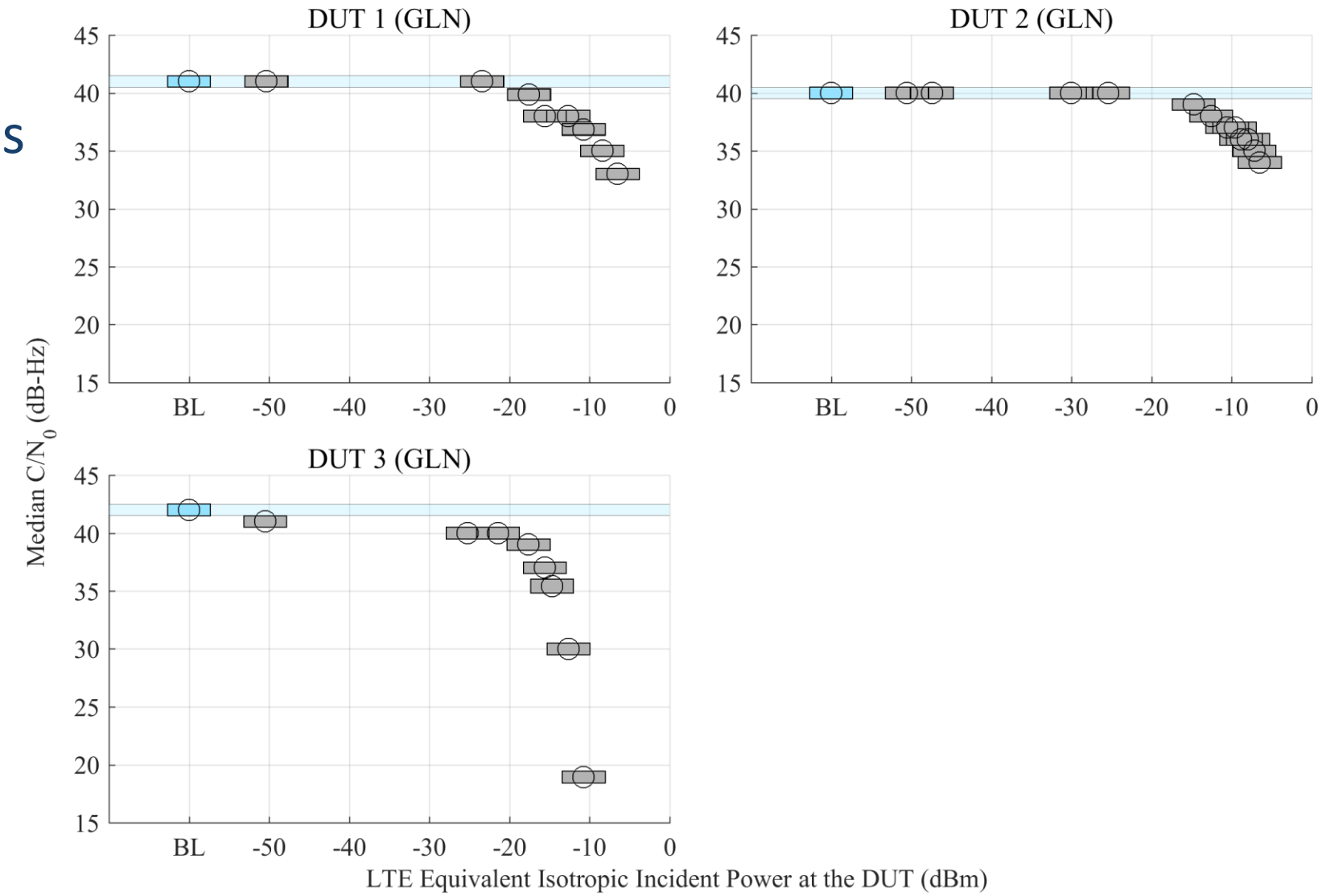

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Fig. 6.20 – pg. 141

General Location

- 95% confidence regions for median 3D position error
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm

Baseline (BL) – No LTE Power

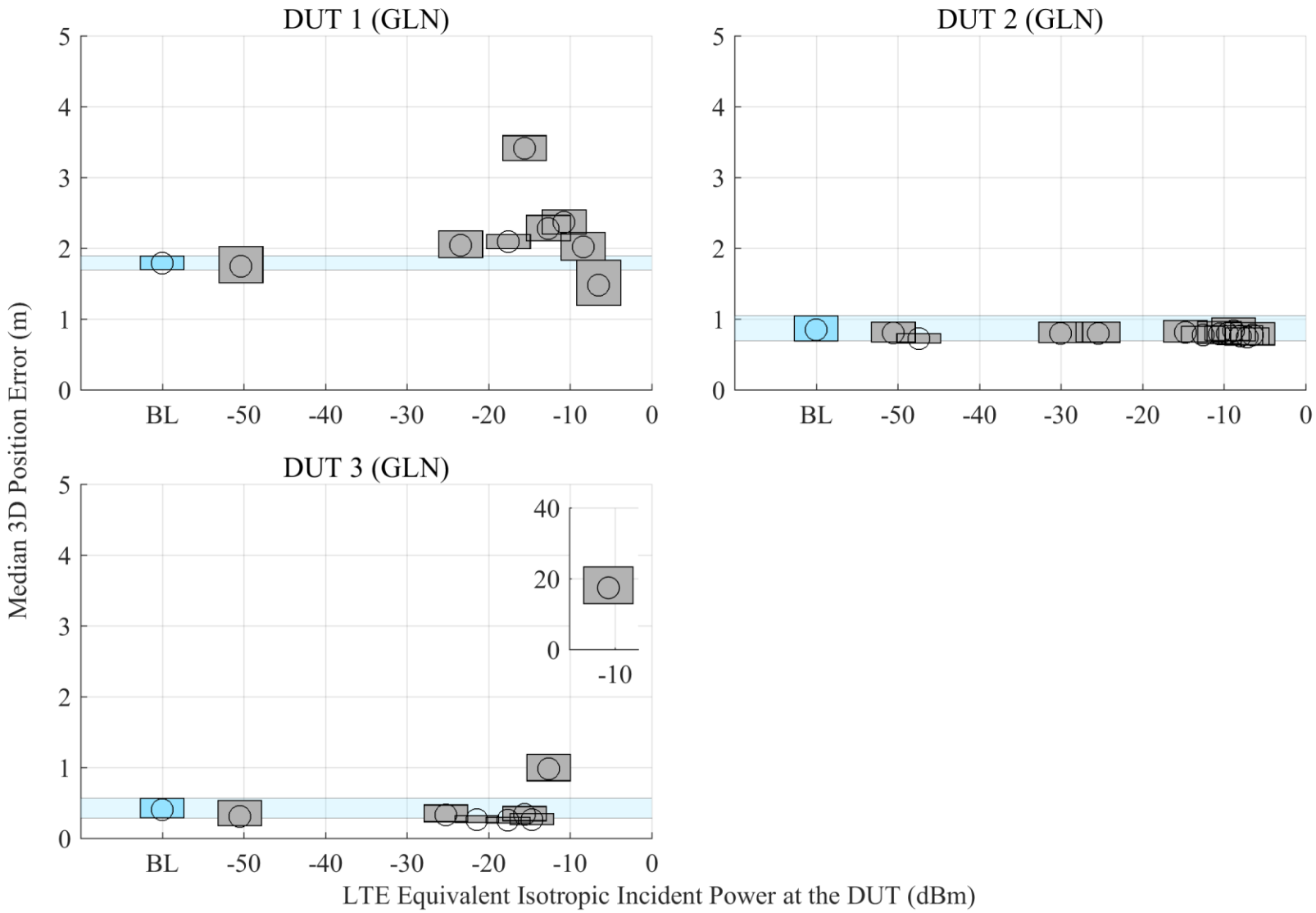

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Fig. 6.22 – pg. 143

General Location

- Number of reported satellites in view scatter plot
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm

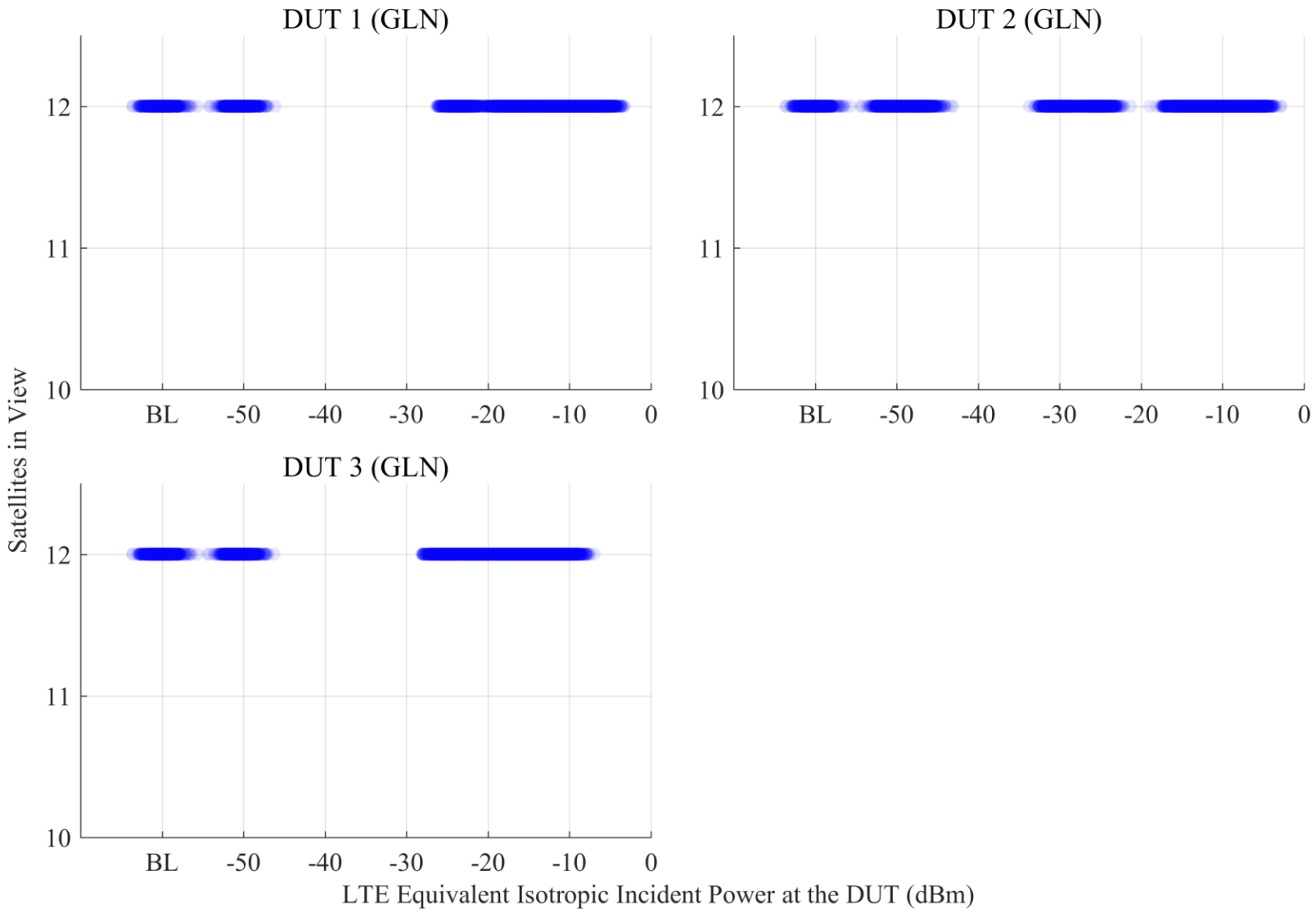

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Fig. 6.23 – pg. 144

Precision Location and Real Time Kinematic

Nominal Satellite Constellation

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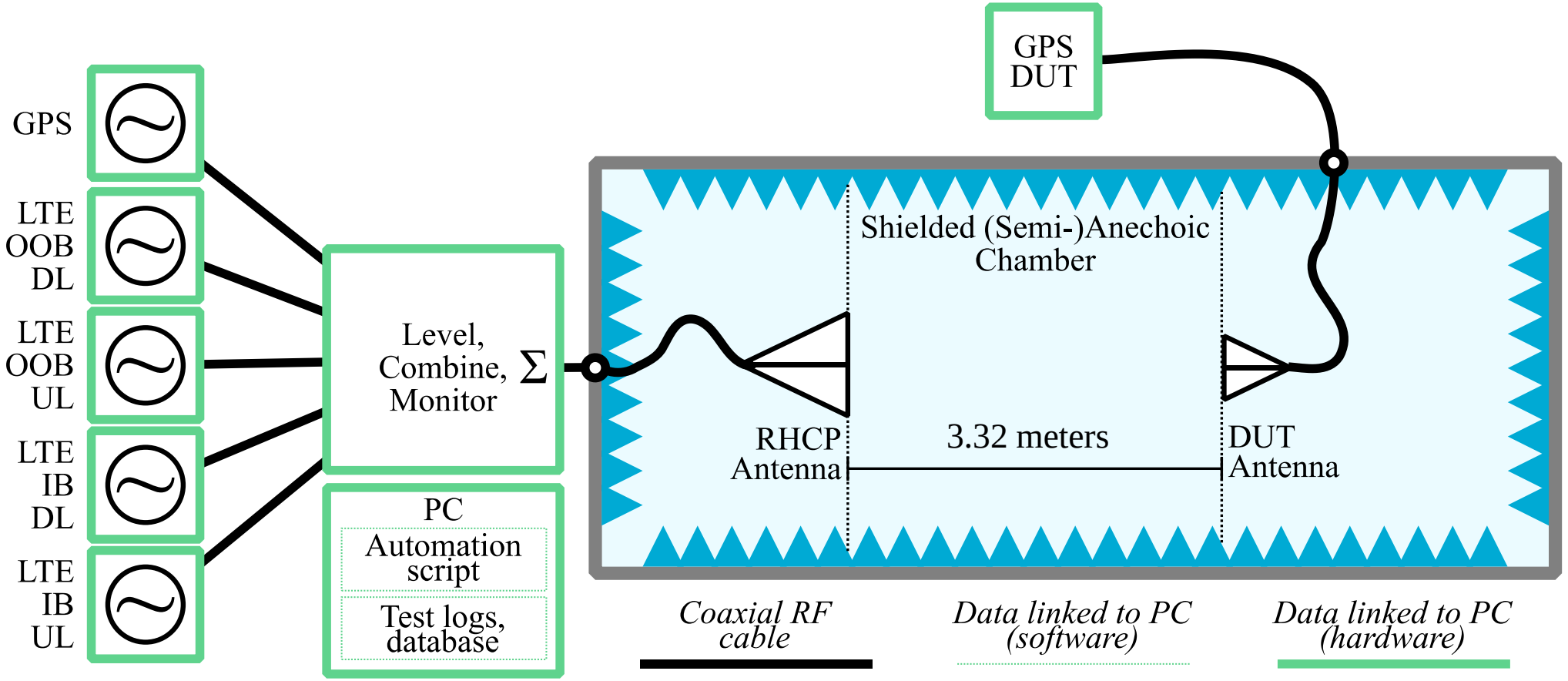
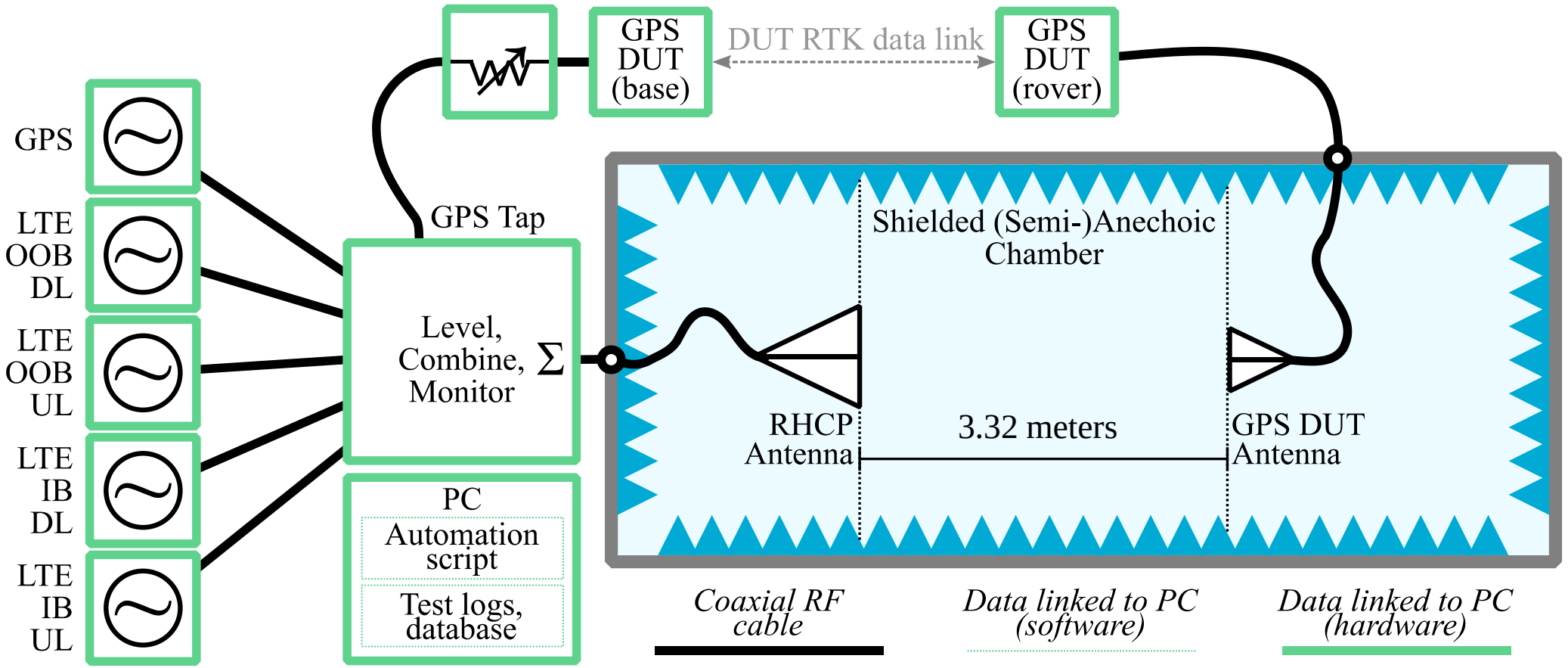
Precision Location Setup

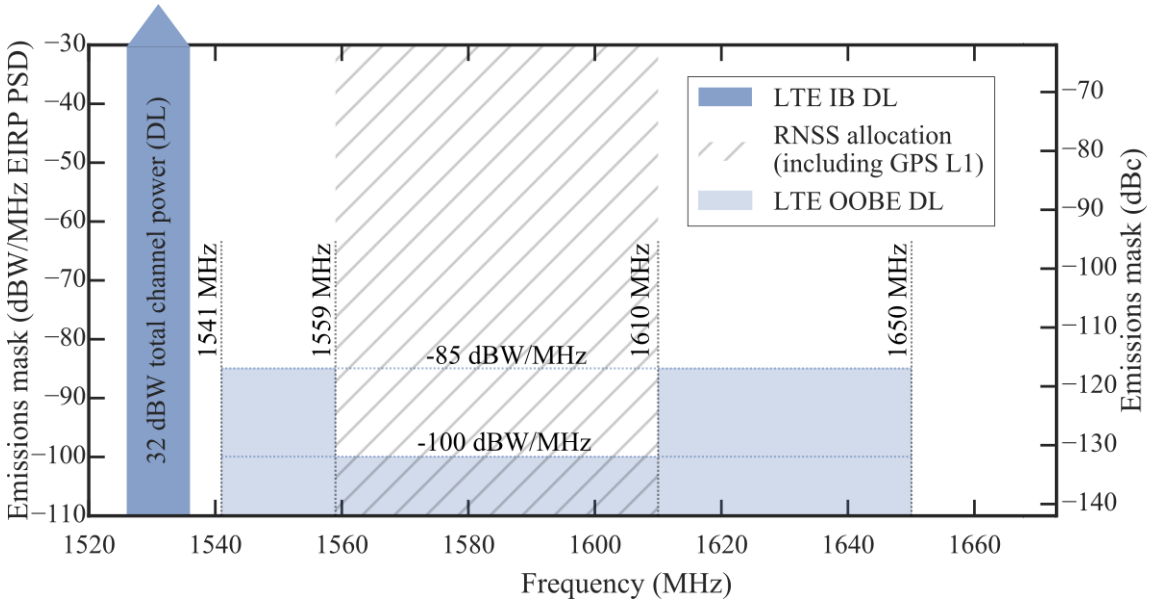


Real Time Kinematic Setup



Precision Location

- Nominal Satellite Condition
  - **Downlink**
  - Uplink 1
  - Uplink 2
  - Combo DL + UL1



Precision Location

- C/N0 scatter plots
- Downlink
- Nominal satellite condition
- 1200 points per LTE power level per satellite

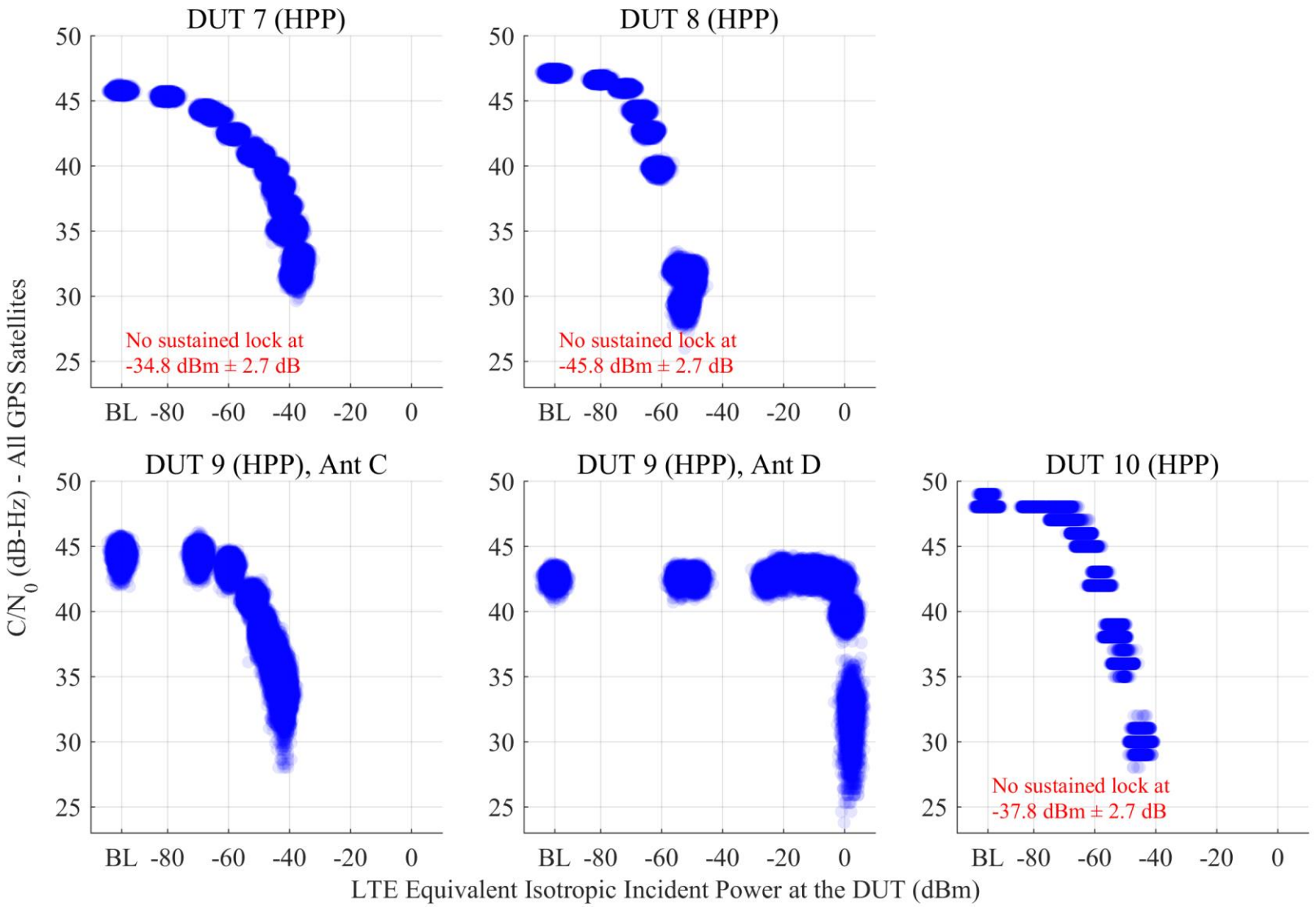


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Fig. 6.24 – pg. 145

Precision Location

- 3D position error scatter plots
- Downlink
- Nominal satellite condition

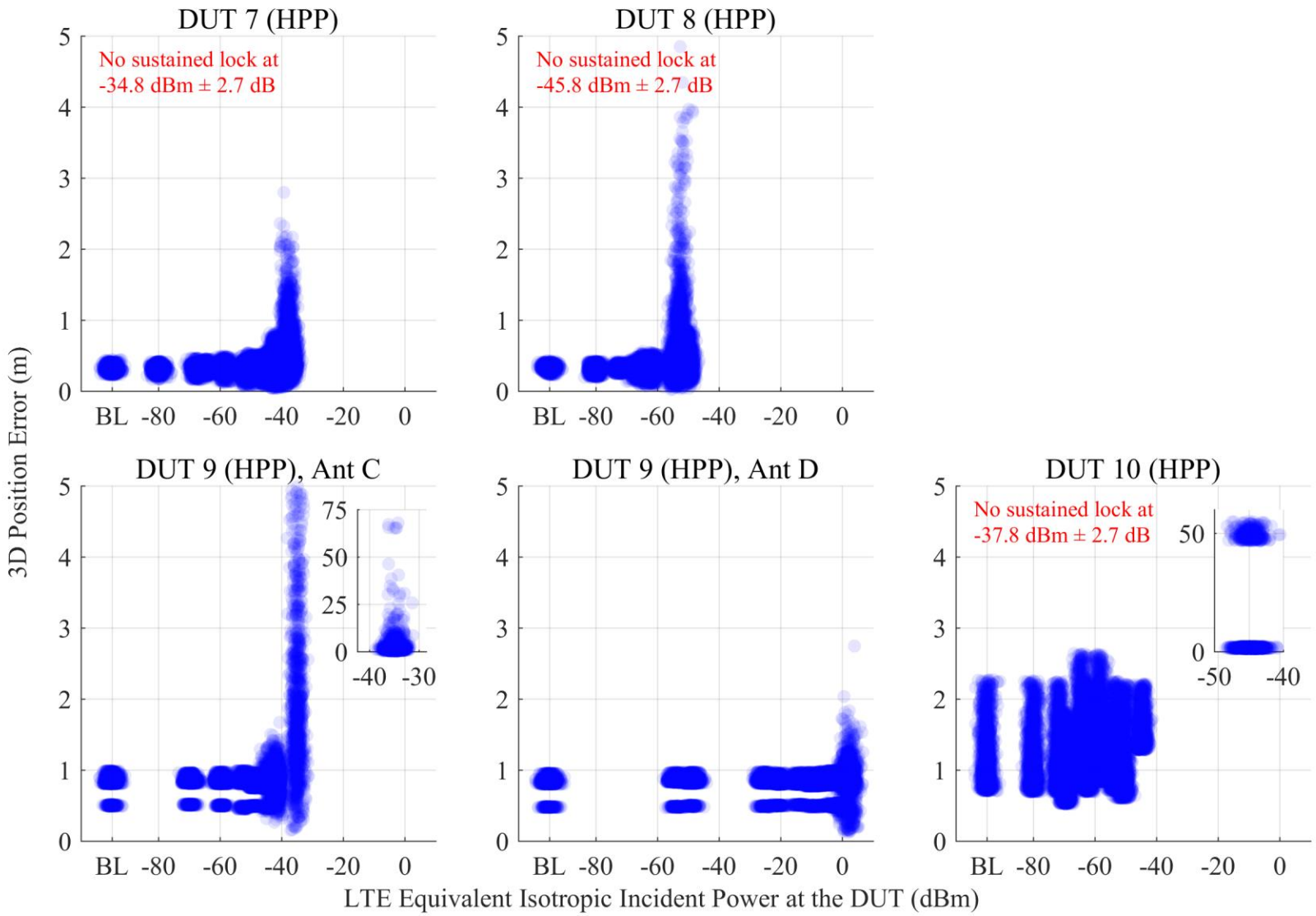

Fig. 6.26 – pg. 147

Precision Location

- 95% confidence regions for median C/N_0
- Downlink
- Nominal satellite condition

Baseline (BL) – No LTE Power

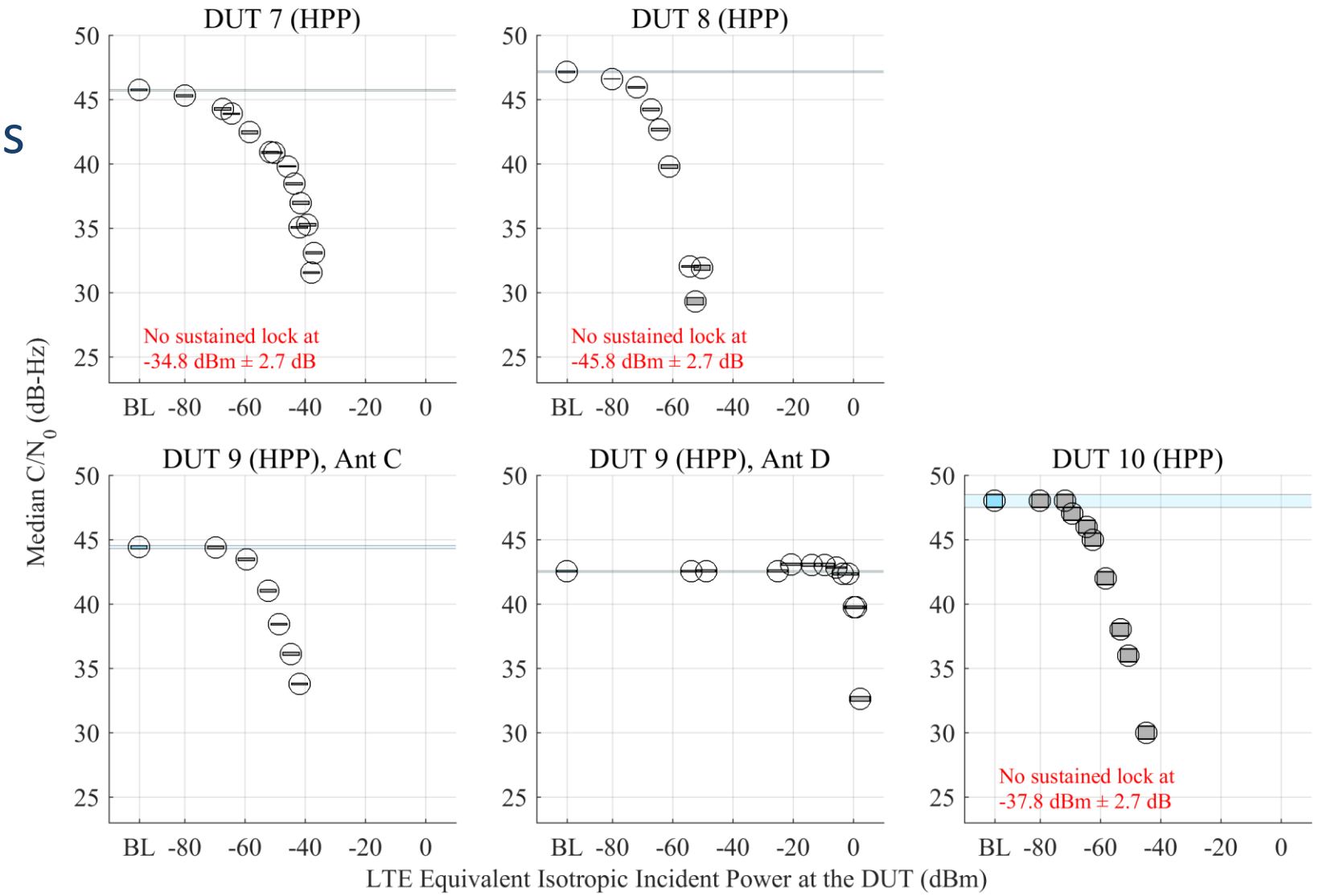

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Fig. 6.25 – pg. 146

Precision Location

- 95% confidence regions for median 3D position error
- Downlink
- Nominal satellite condition

Baseline (BL) – No LTE Power

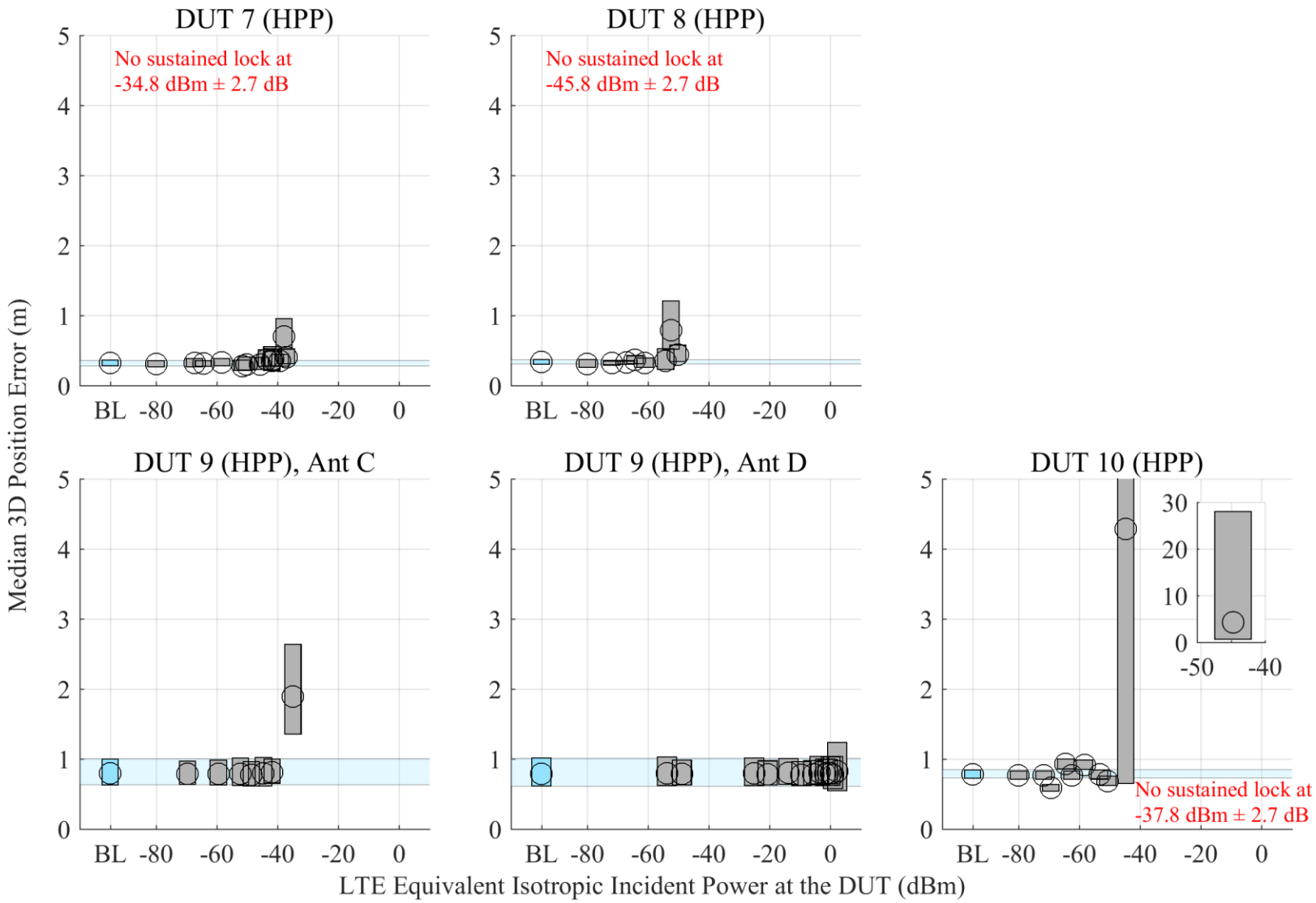

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Fig. 6.27 – pg. 148

Precision Location

- Number of reported satellites in view scatter plot
- Downlink
- Nominal satellite condition

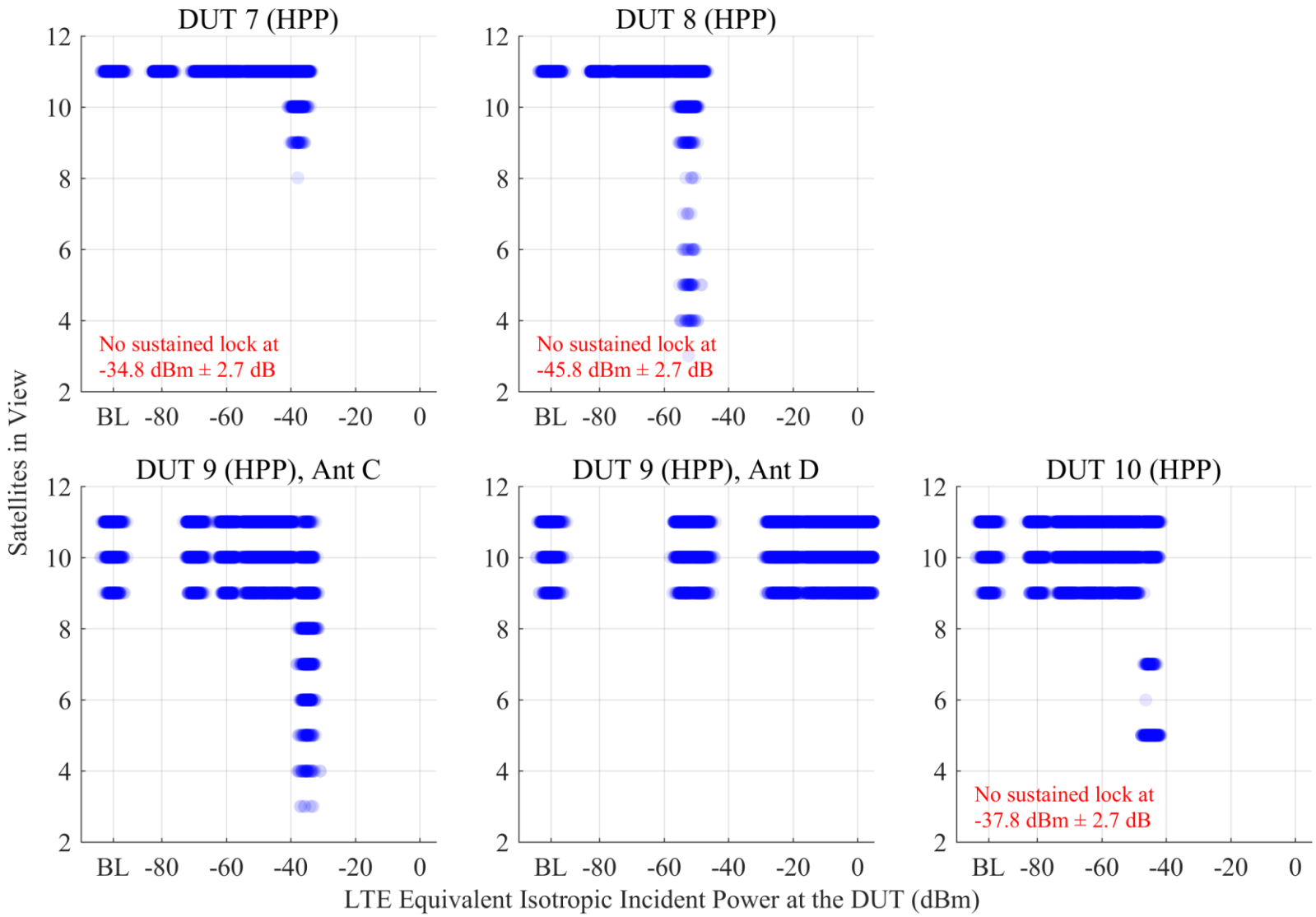

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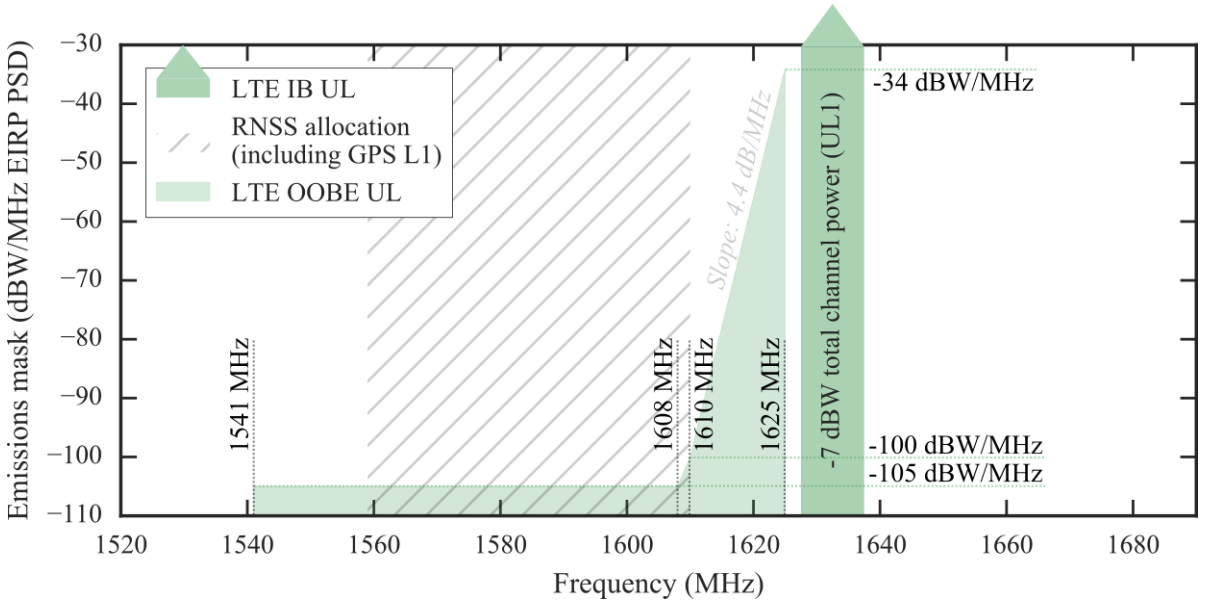
Fig. 6.28 – pg. 149

Precision Location

- Nominal Satellite Condition
  - Downlink
  - **Uplink 1**
  - Uplink 2
  - Combo DL + UL1



Precision Location

- C/N0 scatter plots
- Uplink 1
- Nominal satellite condition
- 1200 points per LTE power level per satellite

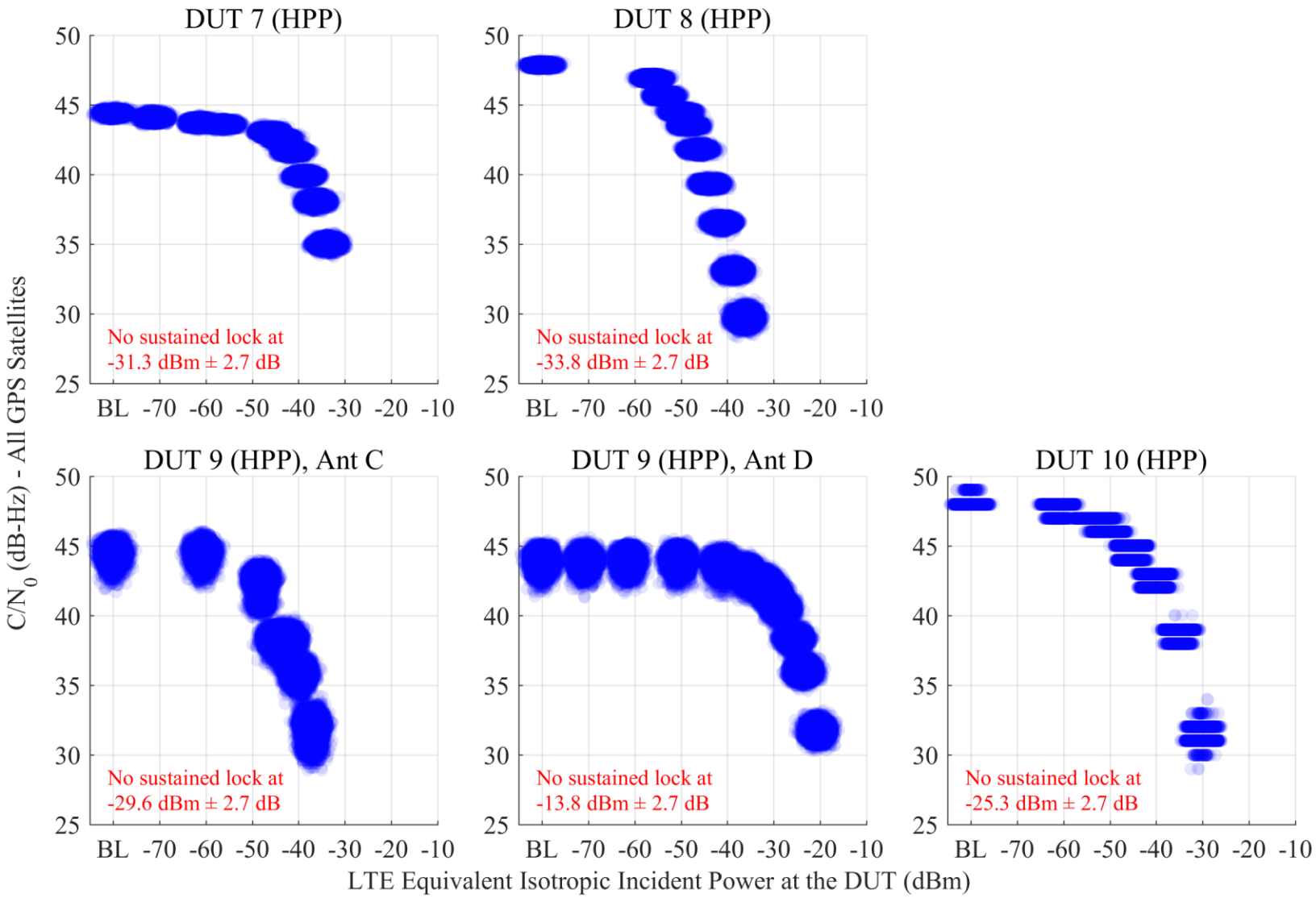


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Fig. 6.29 – pg. 150

Precision Location

- 3D position error scatter plots
- Uplink 1
- Nominal satellite condition

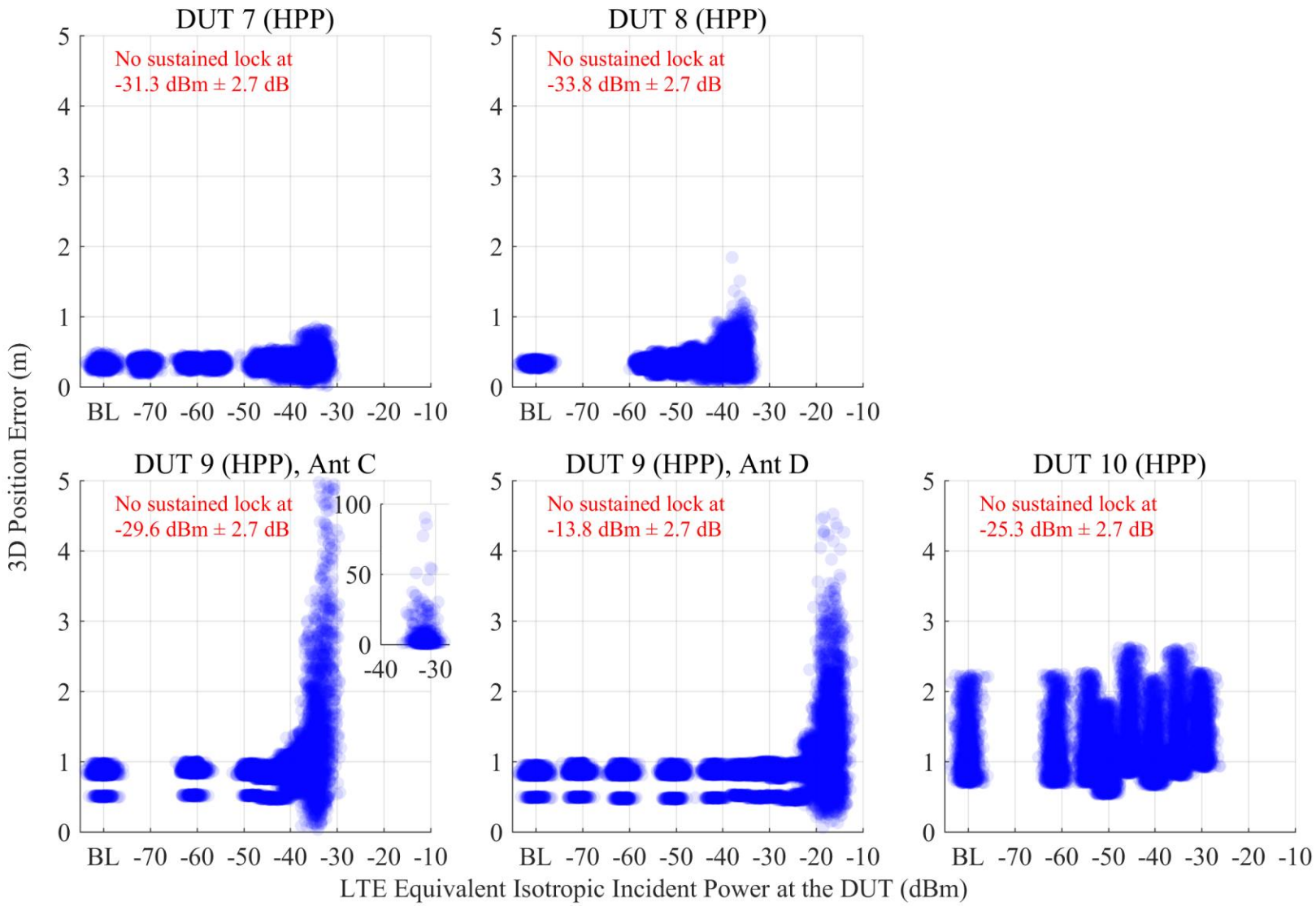

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Fig. 6.31 – pg. 152

Precision Location

- 95% confidence regions for median C/N_0
- Uplink 1
- Nominal satellite condition

Baseline (BL) – No LTE Power

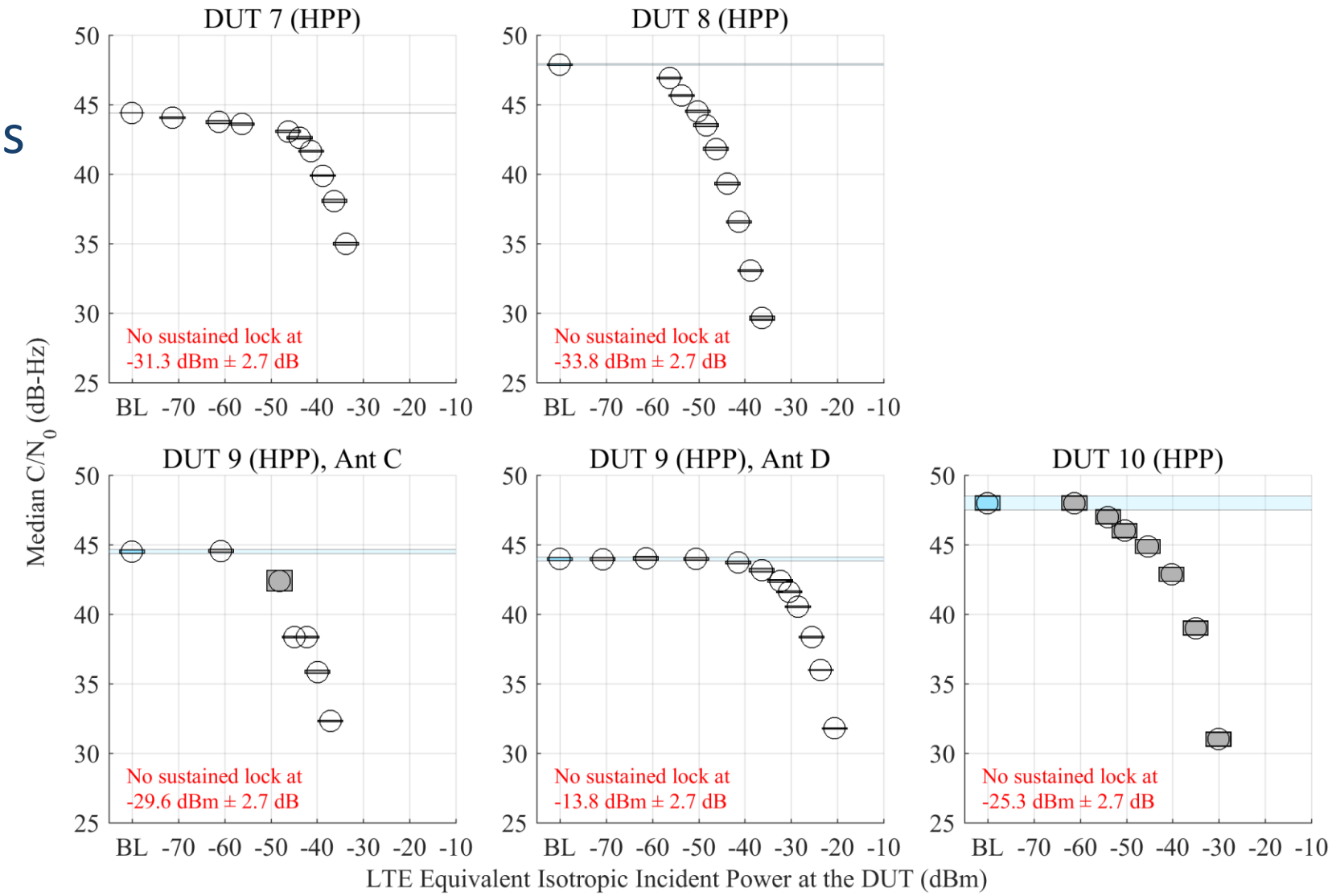

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Fig. 6.30 – pg. 151

Precision Location

- 95% confidence regions for median 3D position error
- Uplink 1
- Nominal satellite condition

Baseline (BL) – No LTE Power

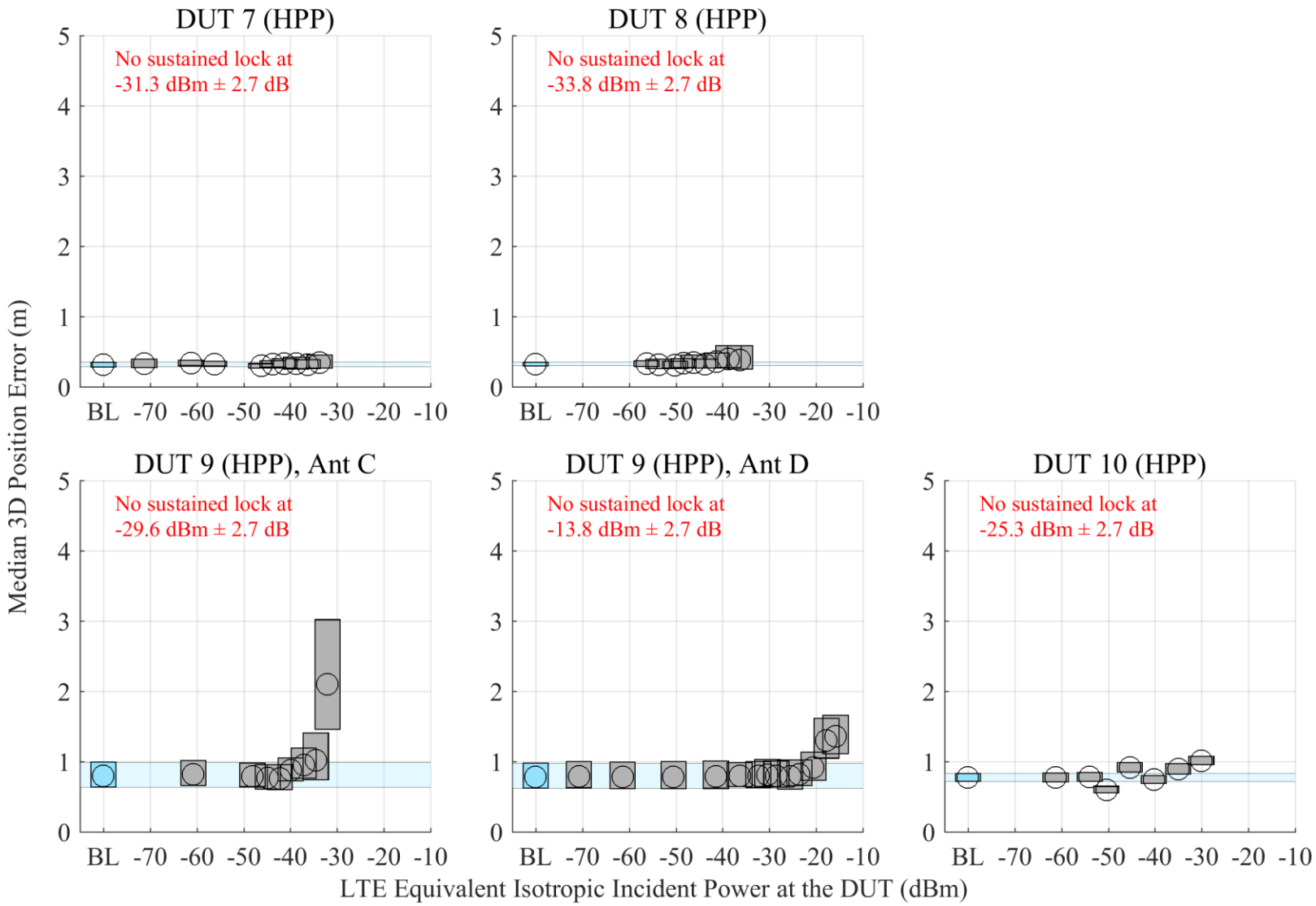

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Fig. 6.32 – pg. 153

Precision Location

- Number of reported satellites in view scatter plot
- Uplink 1
- Nominal satellite condition

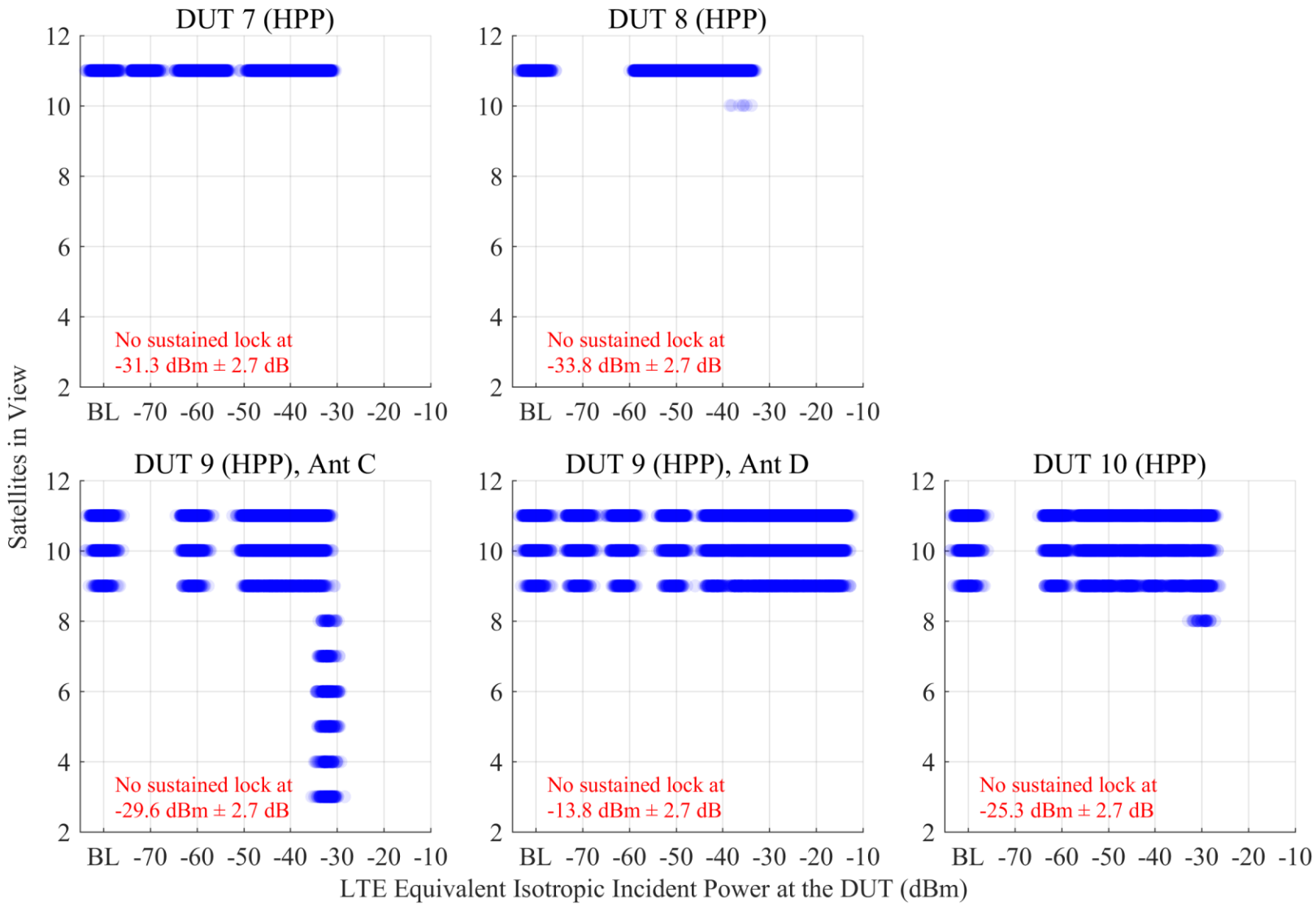

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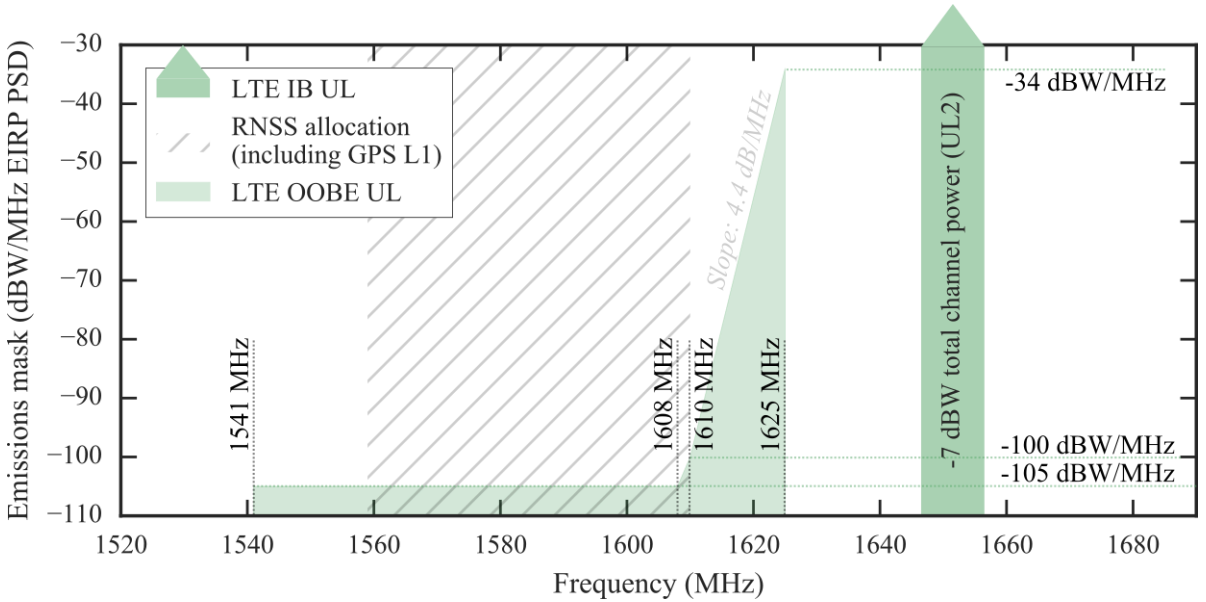
Fig. 6.33 – pg. 154

Precision Location

- Nominal Satellite Condition
  - Downlink
  - Uplink 1
  - **Uplink 2**
  - Combo DL + UL1



Precision Location

- C/N0 scatter plots
- Uplink 2
- Nominal satellite condition
- 1200 points per LTE power level per satellite

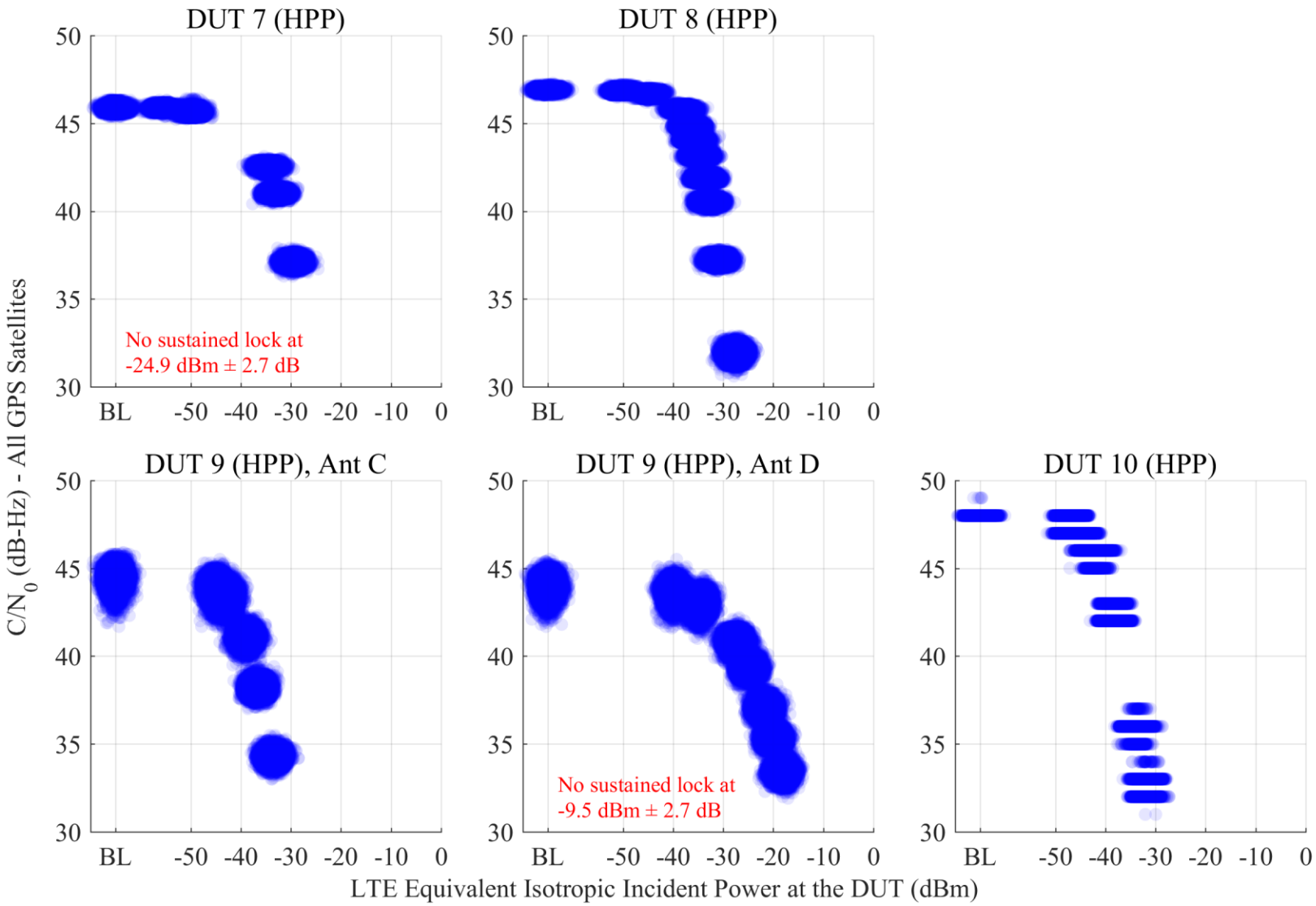


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Fig. 6.34 – pg. 155

Precision Location

- 3D position error scatter plots
- Uplink 2
- Nominal satellite condition

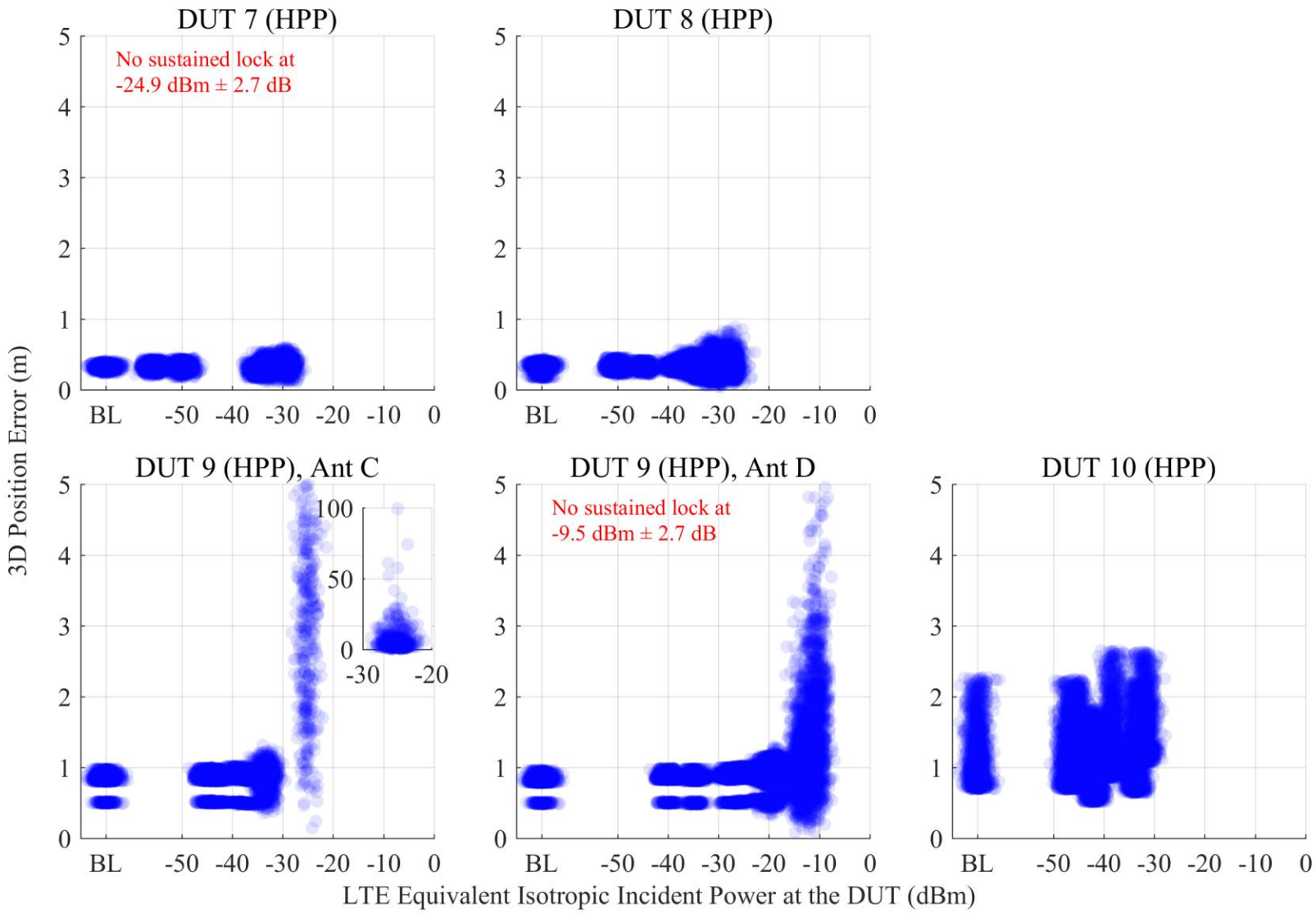

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Fig. 6.36 – pg. 157

Precision Location

- 95% confidence regions for median C/N_0
- Uplink 2
- Nominal satellite condition

Baseline (BL) – No LTE Power

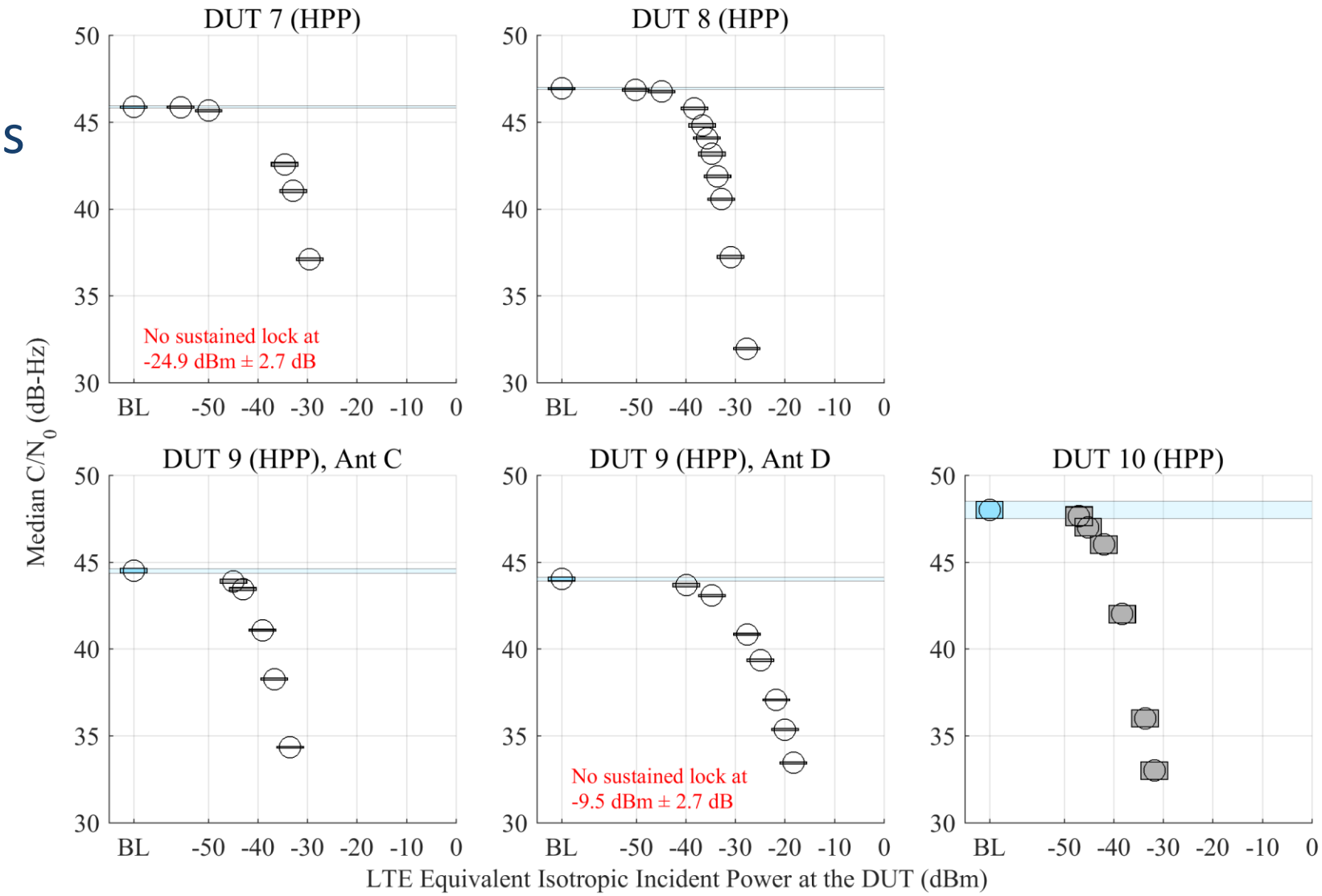

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Fig. 6.35 – pg. 156

Precision Location

- 95% confidence regions for median 3D position error
- Uplink 2
- Nominal satellite condition

Baseline (BL) – No LTE Power

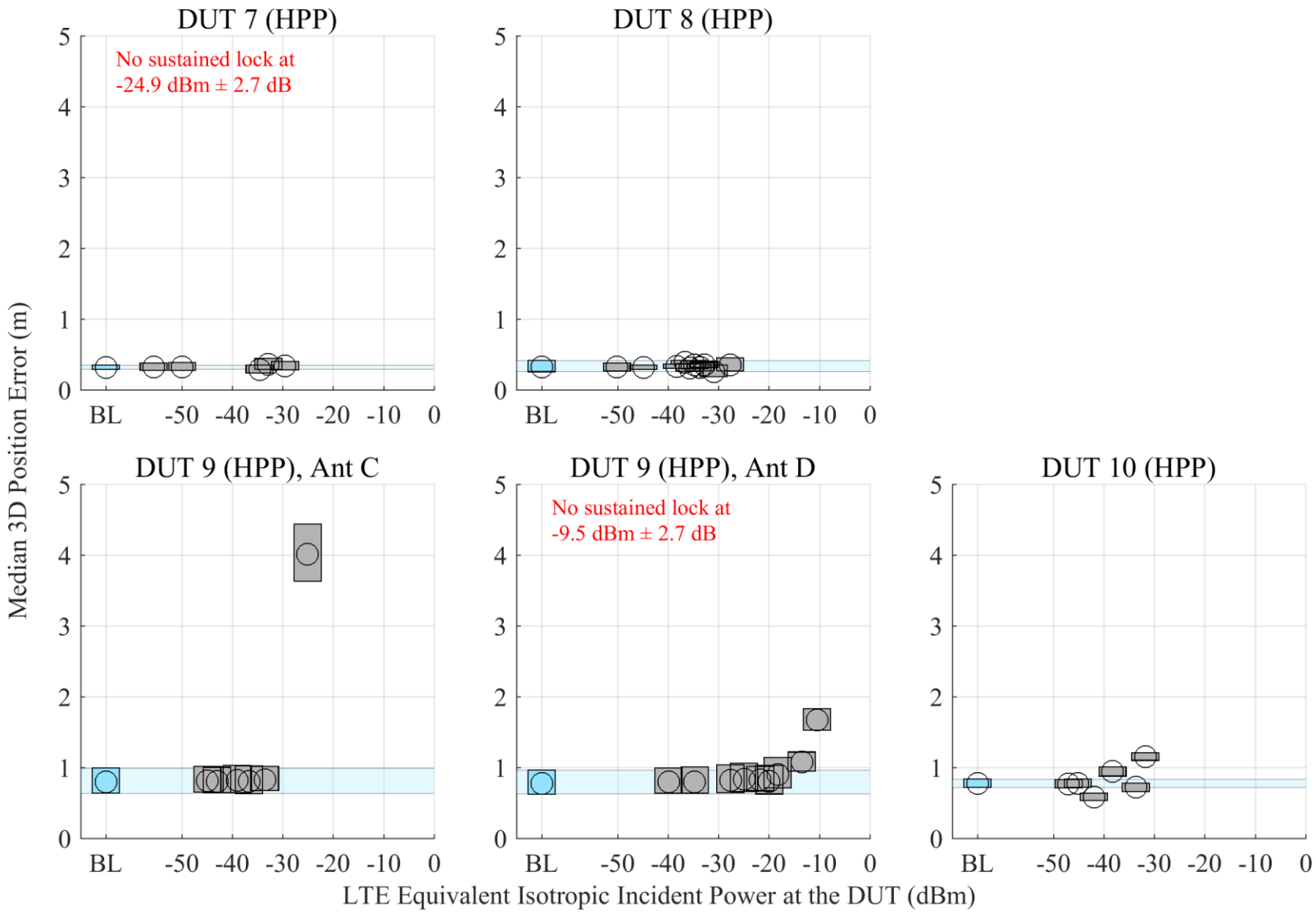

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Fig. 6.37 – pg. 158

Precision Location

- Number of reported satellites in view scatter plot
- Uplink 2
- Nominal satellite condition

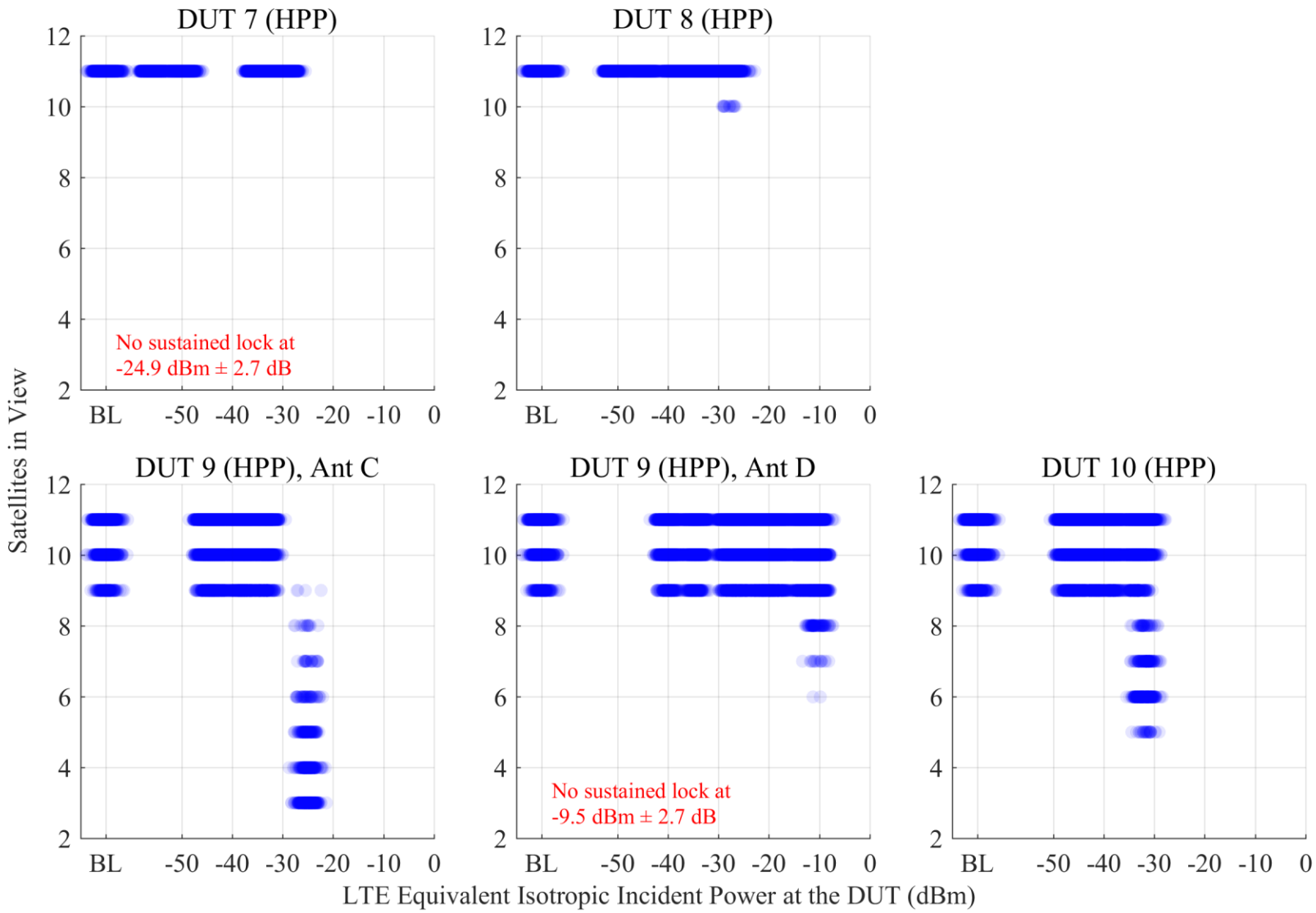

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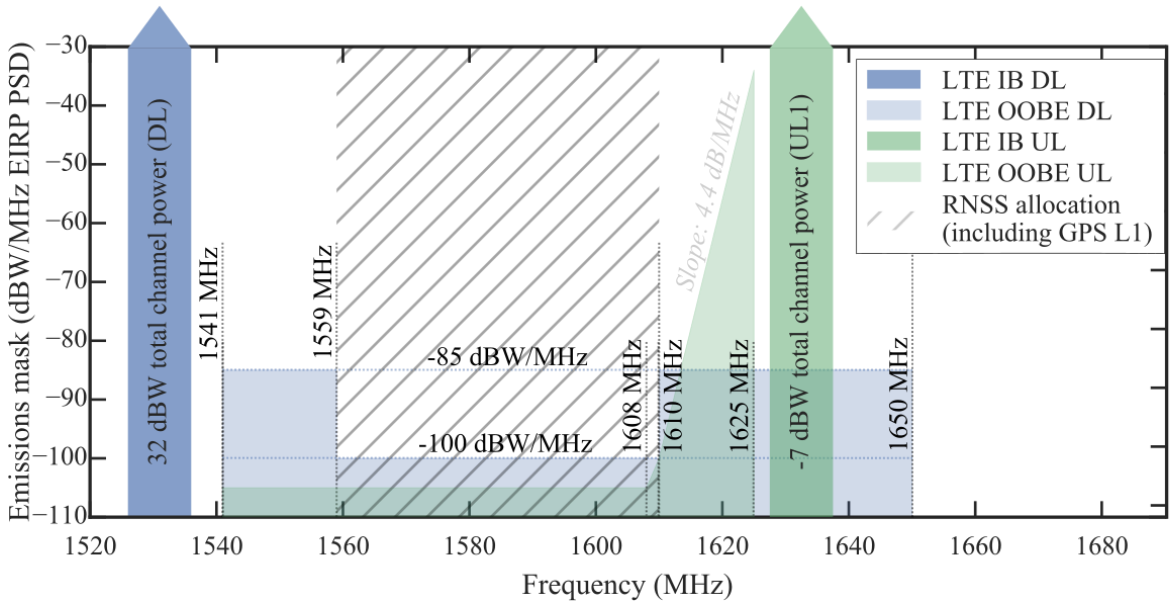
Fig. 6.38 – pg. 159

Precision Location

- Nominal Satellite Condition
  - Downlink
  - Uplink 1
  - Uplink 2
  - **Combo DL + UL1**



Precision Location

- C/N0 scatter plots
- Combo DL + UL1
- Nominal satellite condition
- 1200 points per LTE power level per satellite
- DL fixed: -50 dBm
- Low-Level DL: -65 dBm

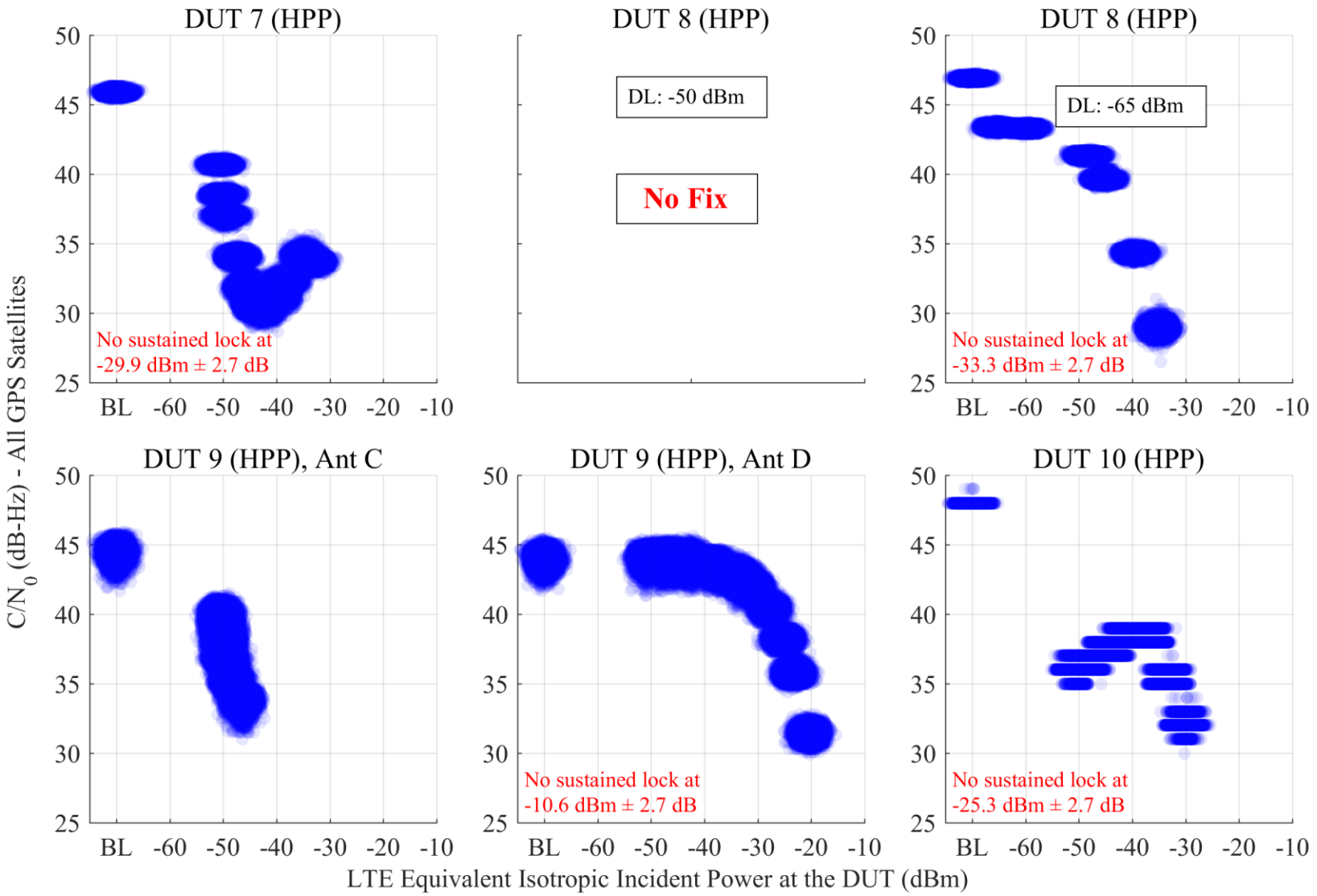


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Fig. 6.39 – pg. 160

Precision Location

- 3D position error scatter plots
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm
- Low-Level DL: -65 dBm

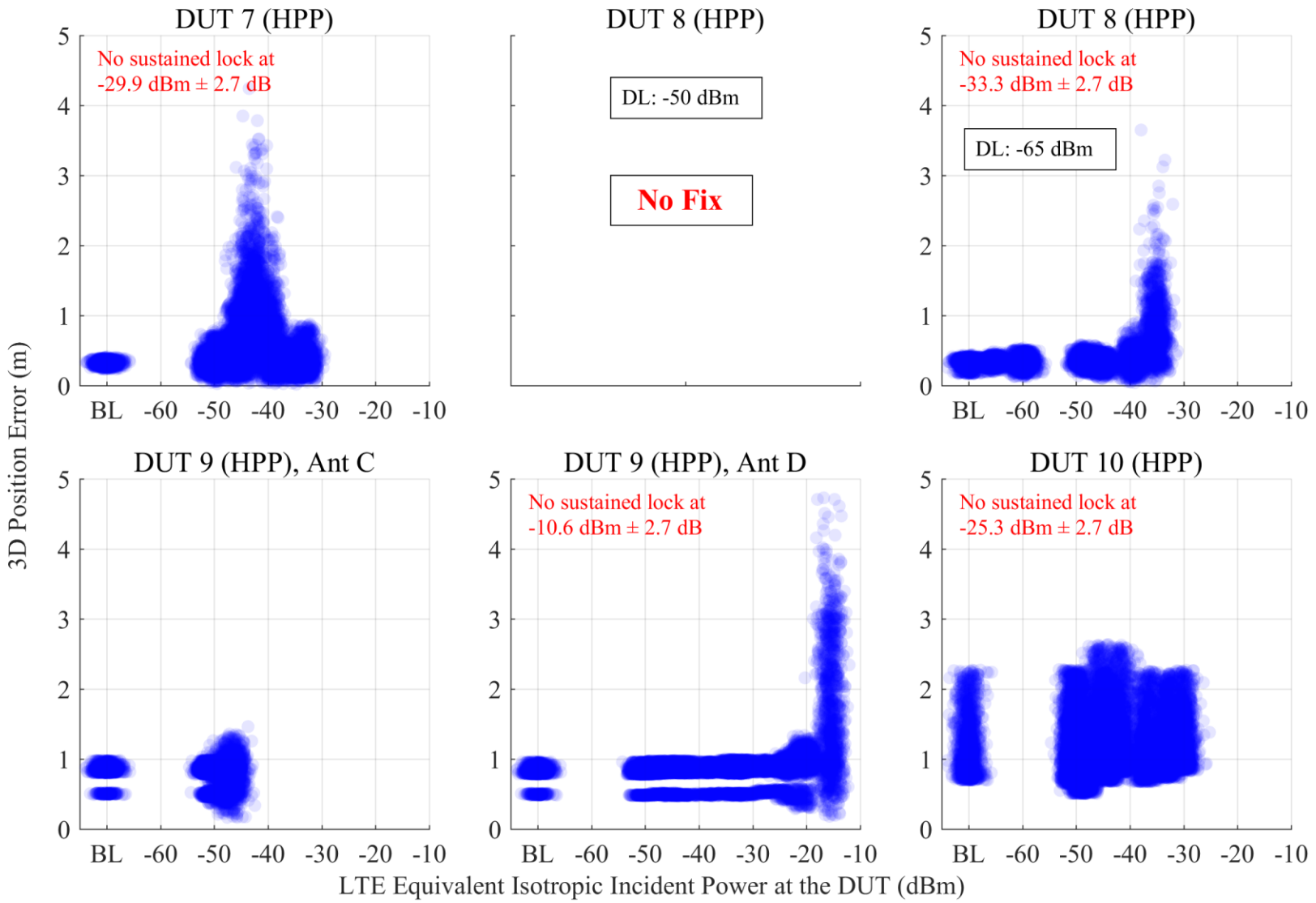

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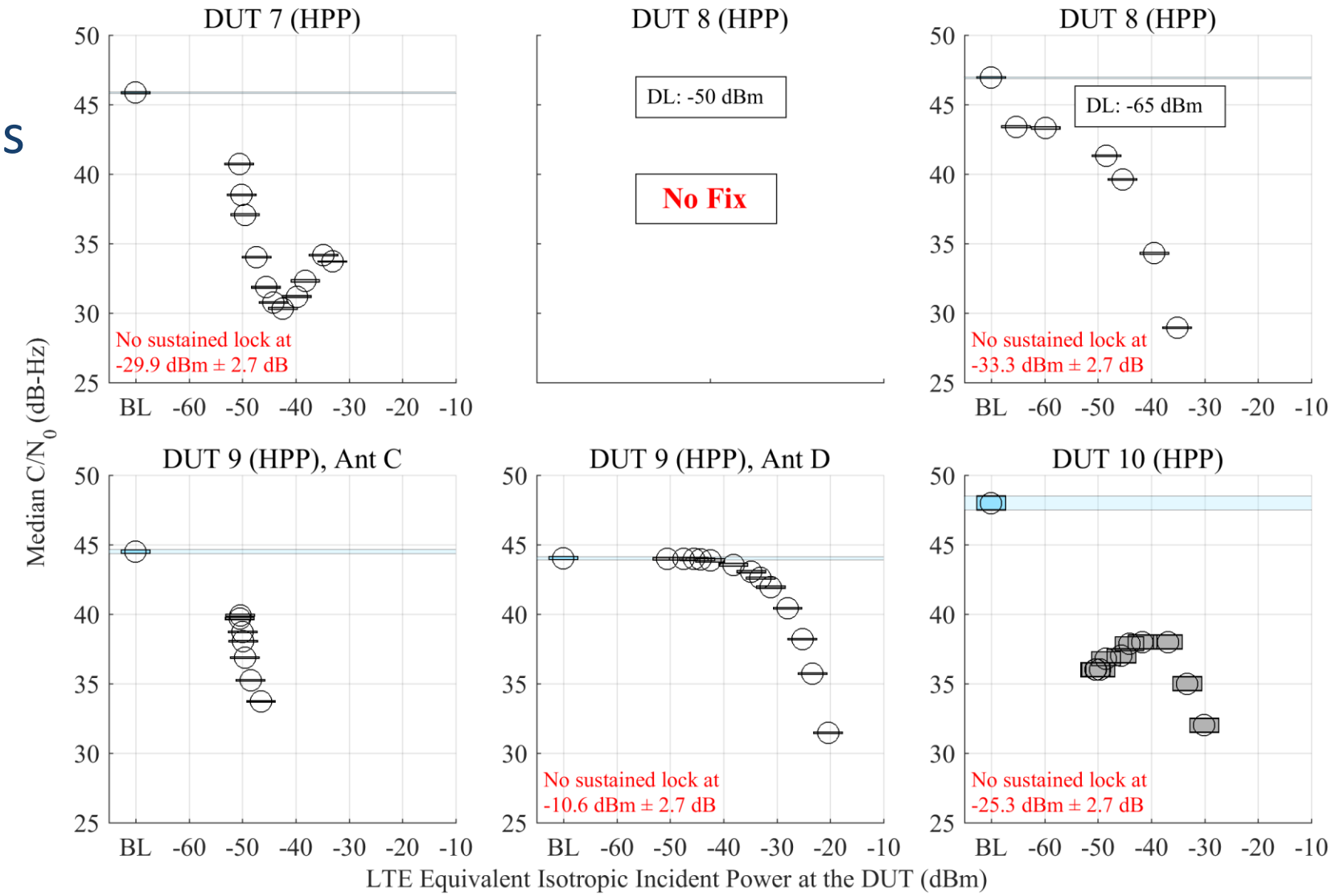
Fig. 6.41 – pg. 162

Precision Location

- 95% confidence regions for median C/N_0
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm
- Low-Level DL: -65 dBm



Baseline (BL) – No LTE Power

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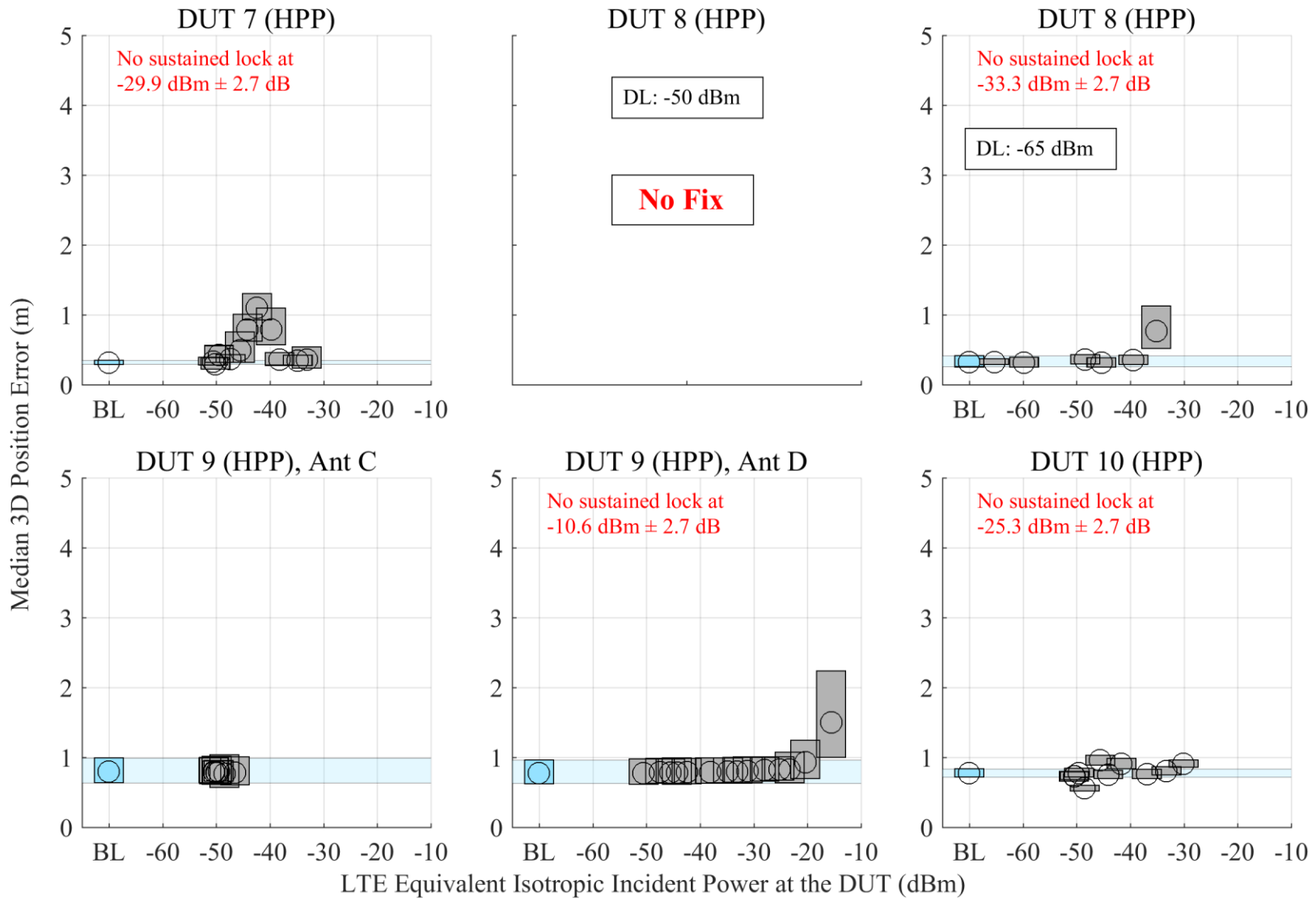
Fig. 6.40 – pg. 161

Precision Location

- 95% confidence regions for median 3D position error
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm
- Low-Level DL: -65 dBm



Baseline (BL) – No LTE Power

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Fig. 6.42 – pg. 163

Precision Location

- Number of reported satellites in view scatter plot
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm
- Low-Level DL: -65 dBm

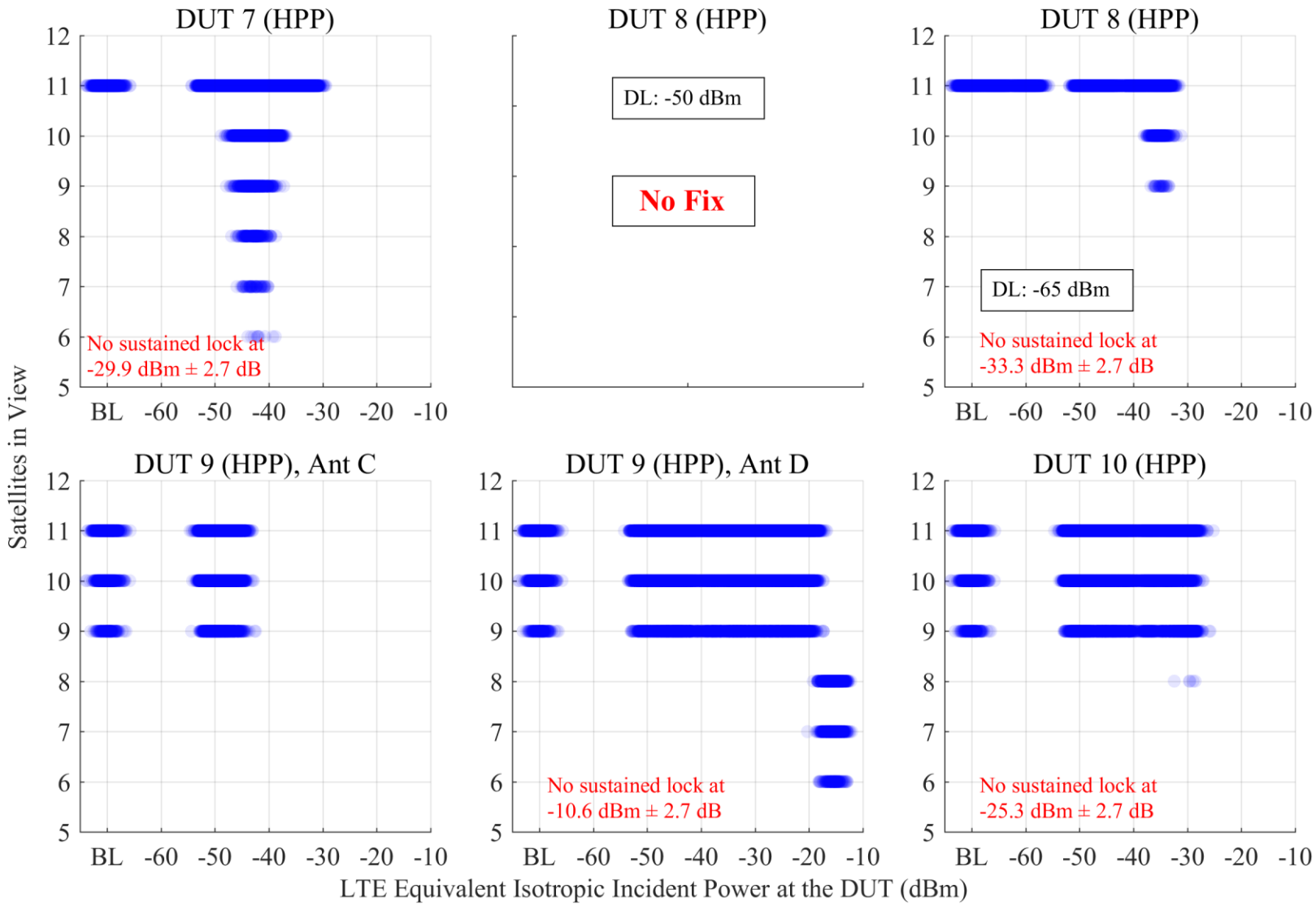

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Fig. 6.43 – pg. 164

Precision Location DUT 7 Repeats

- Measurements a week apart (other DUT tests during that week)

- C/N0 scatter plots (top)
- 95% confidence regions for median C/N_0 (bottom)
- Combo DL + UL1
- DL fixed: -50 dBm
- Nominal satellite condition

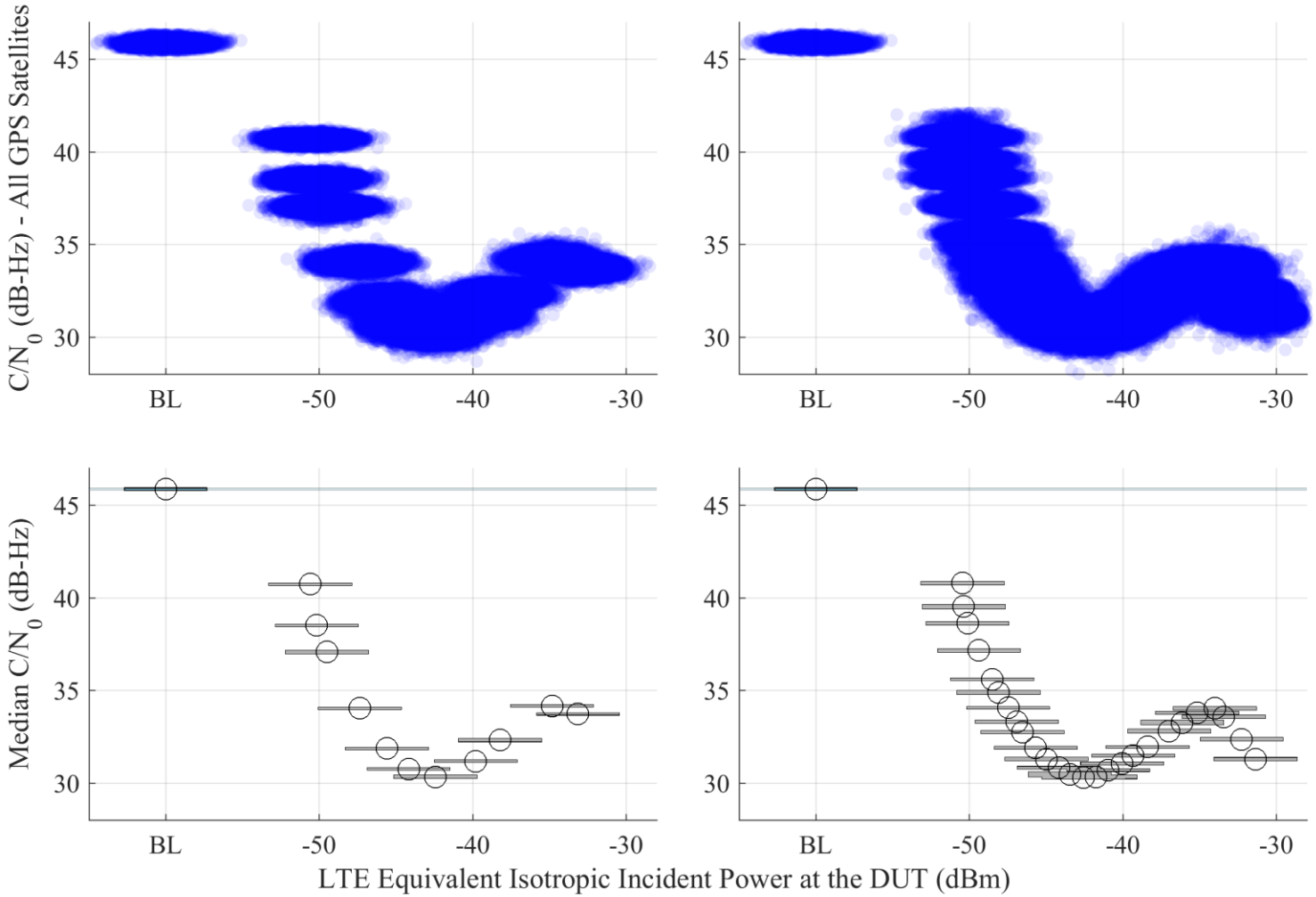

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Fig. 6.45 – pg. 166

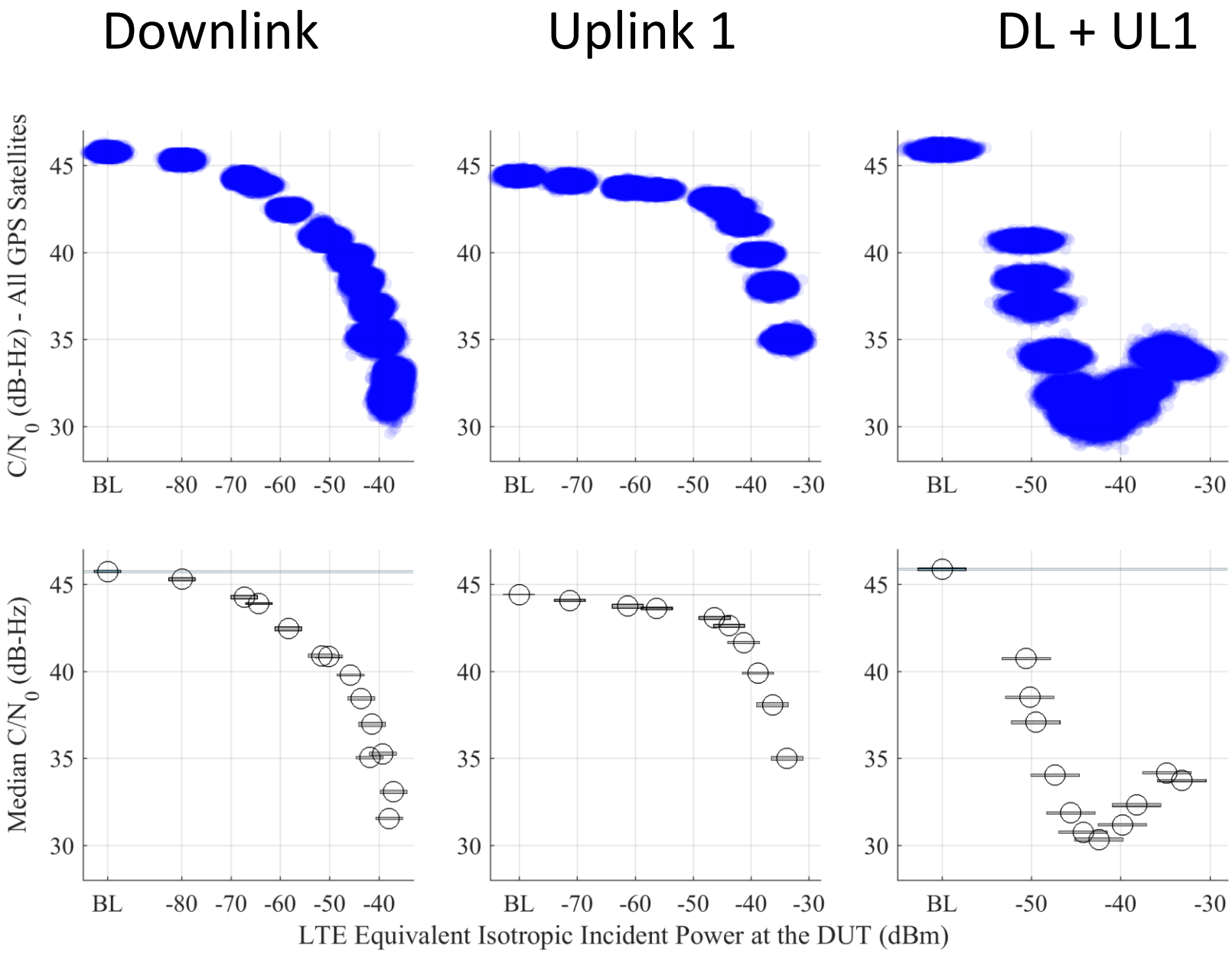

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Fig. 6.44 – pg. 165

Precision Location

DUT 7 Repeats

- DUT measurement repeated
- 3D position error scatter plots (top)
- 95% confidence regions for median 3D position error (bottom)
- Combo DL + UL1
- Nominal satellite condition

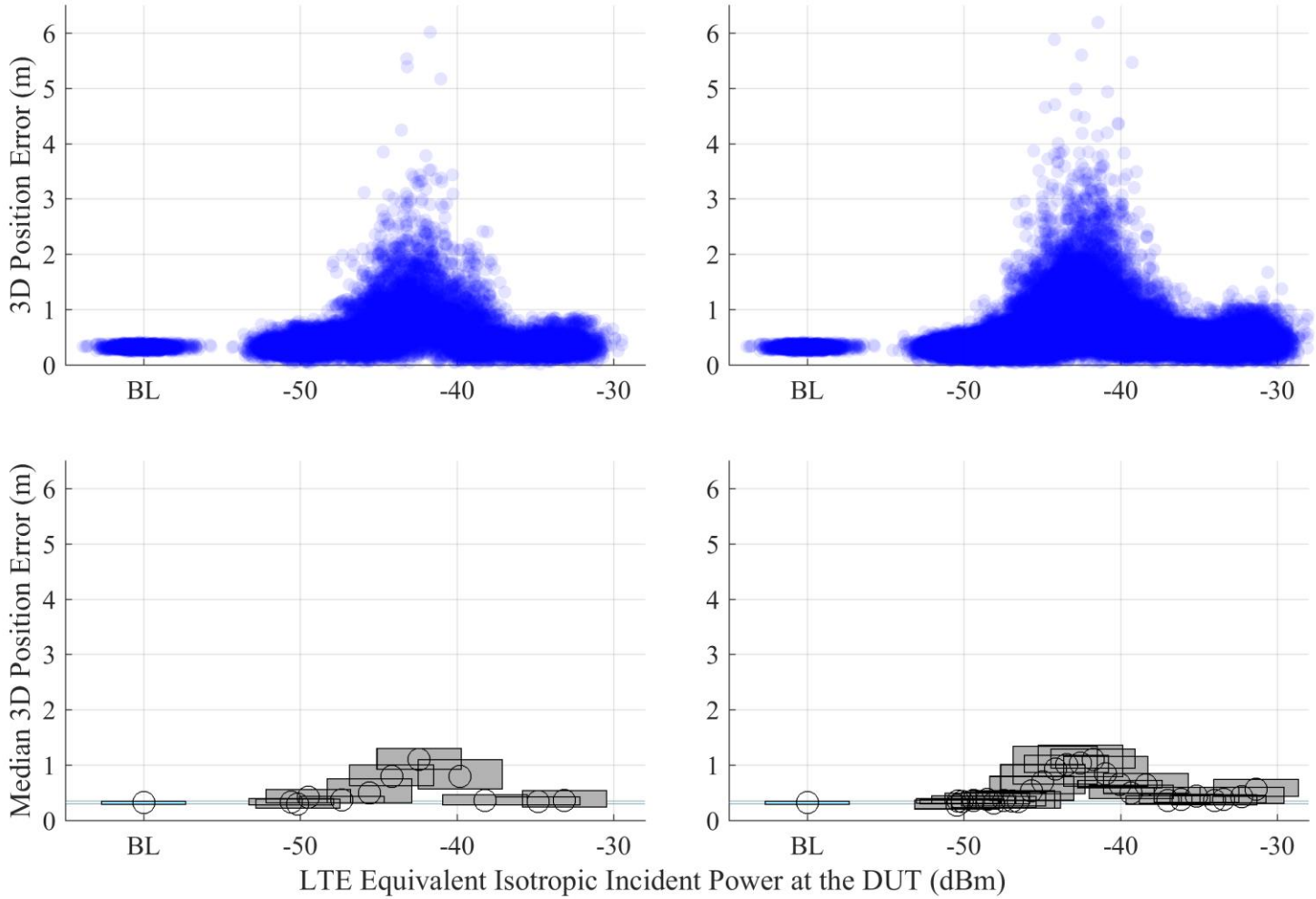

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Fig. 6.47 – pg. 168

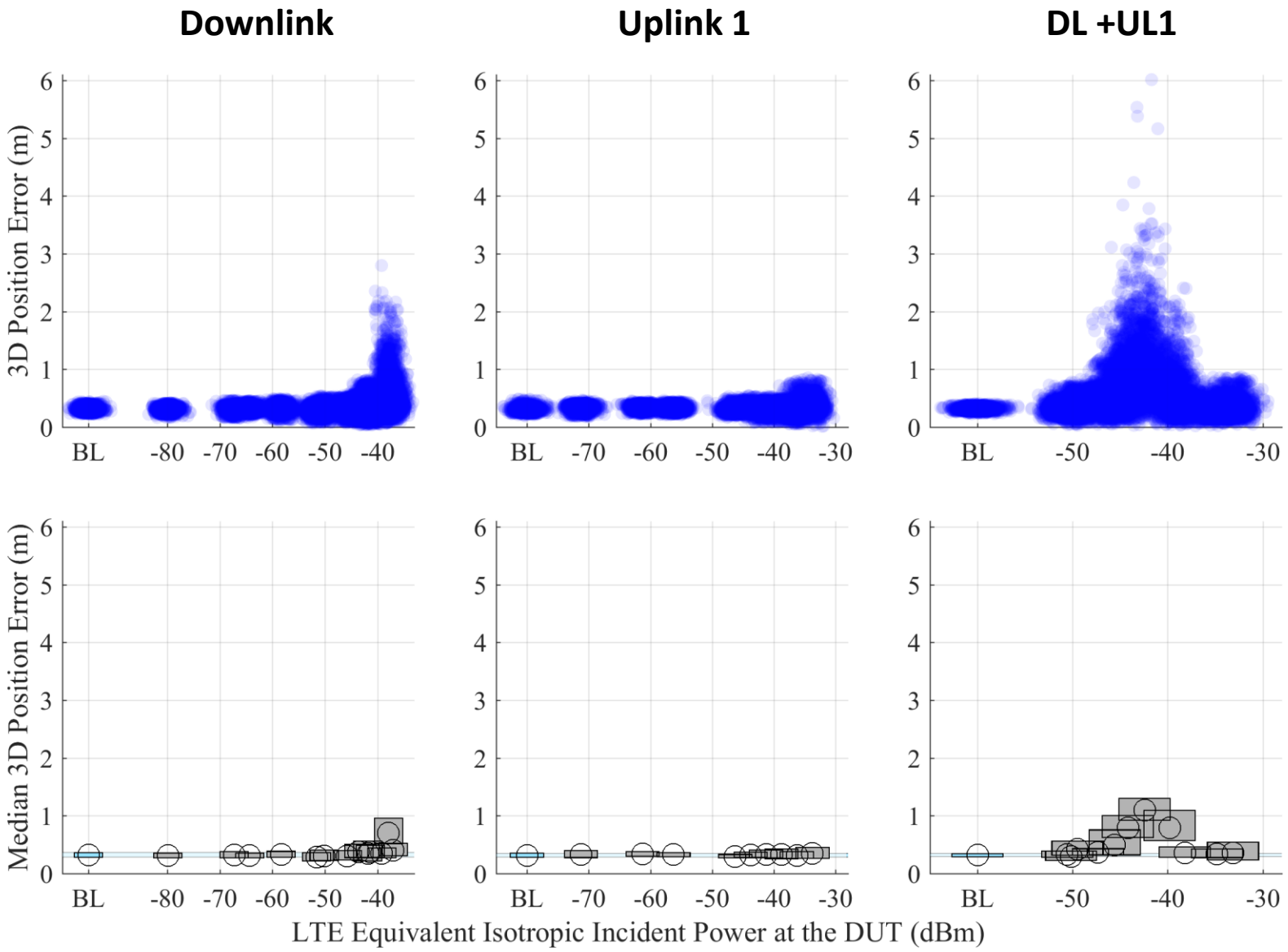

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Fig. 6.46 – pg. 167

Precision Location DUT 7 Repeats

- DUT measurement repeated
- Number of reported satellites in view scatter plot
- Combo DL + UL1
- Nominal satellite condition

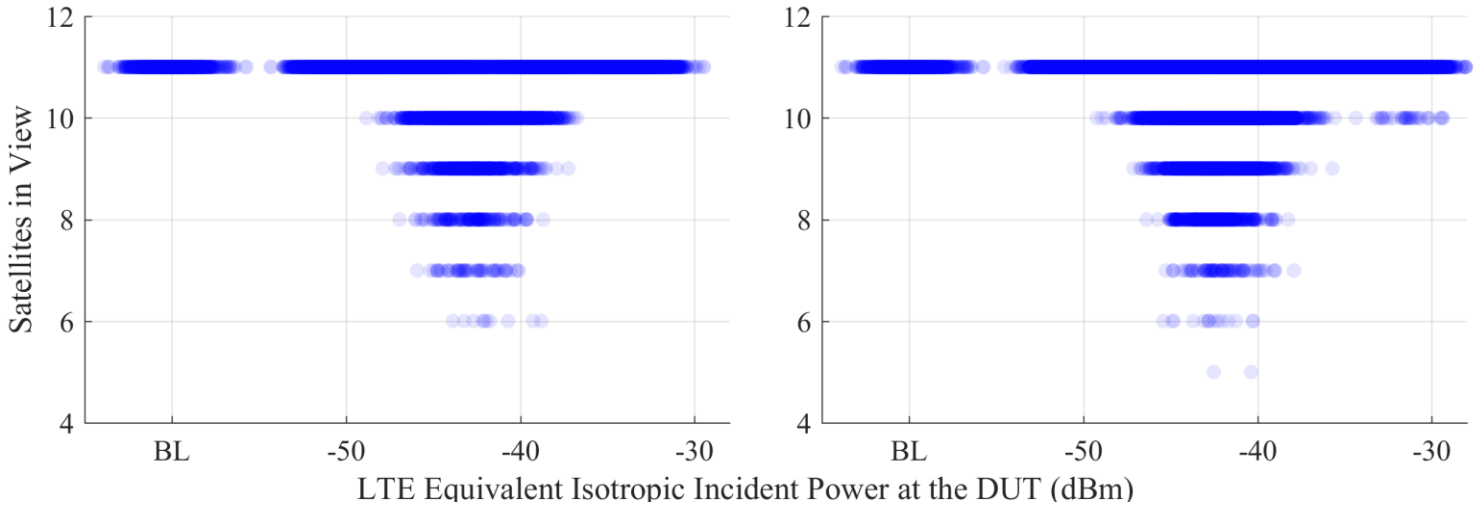

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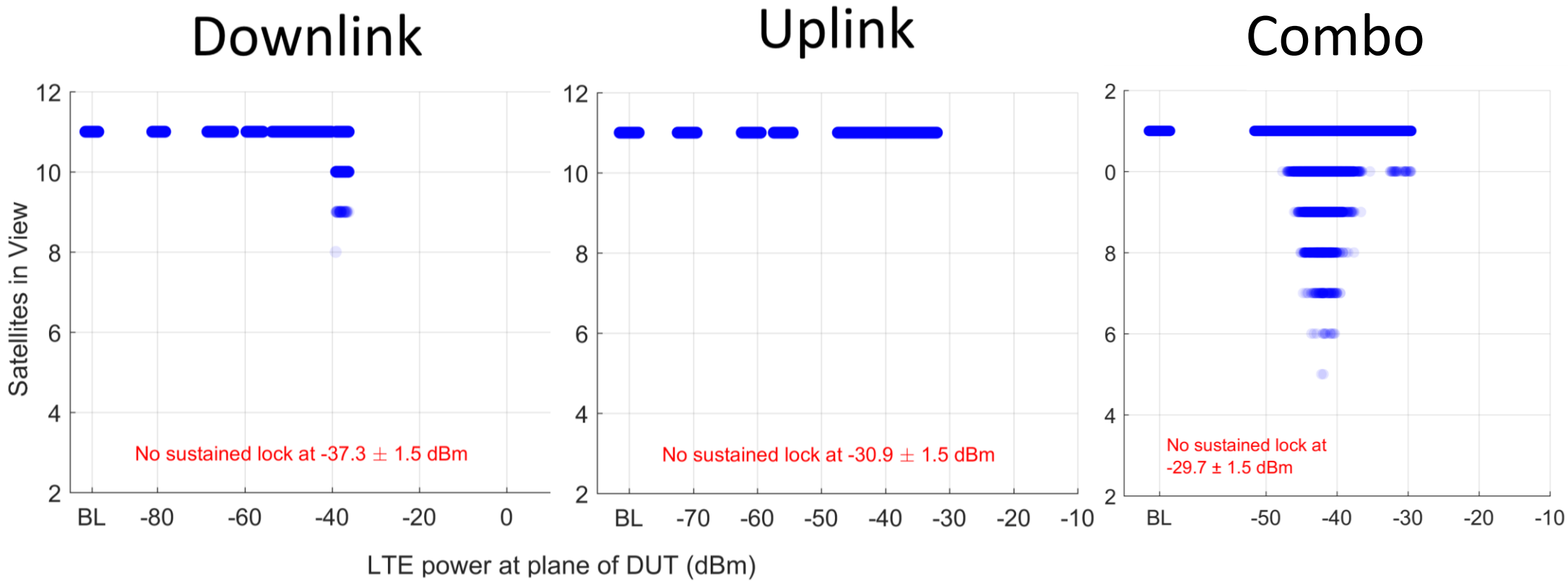
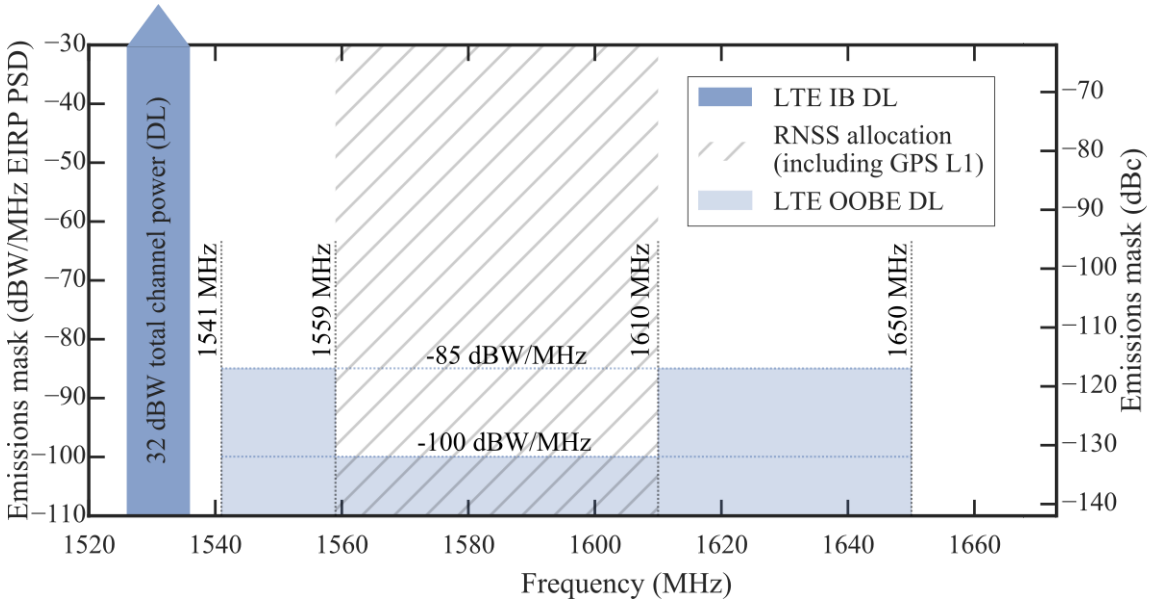
Fig. 6.48 – pg. 169

Precision Location
DUT 7 Repeats



Real Time Kinematic

- Nominal Satellite Condition
  - **Downlink**
  - Uplink 1
  - Uplink 2
  - Combo DL + UL1



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Real Time Kinematic

- C/N0 scatter plots
- Downlink
- Nominal satellite condition
- 1200 points per LTE power level per satellite

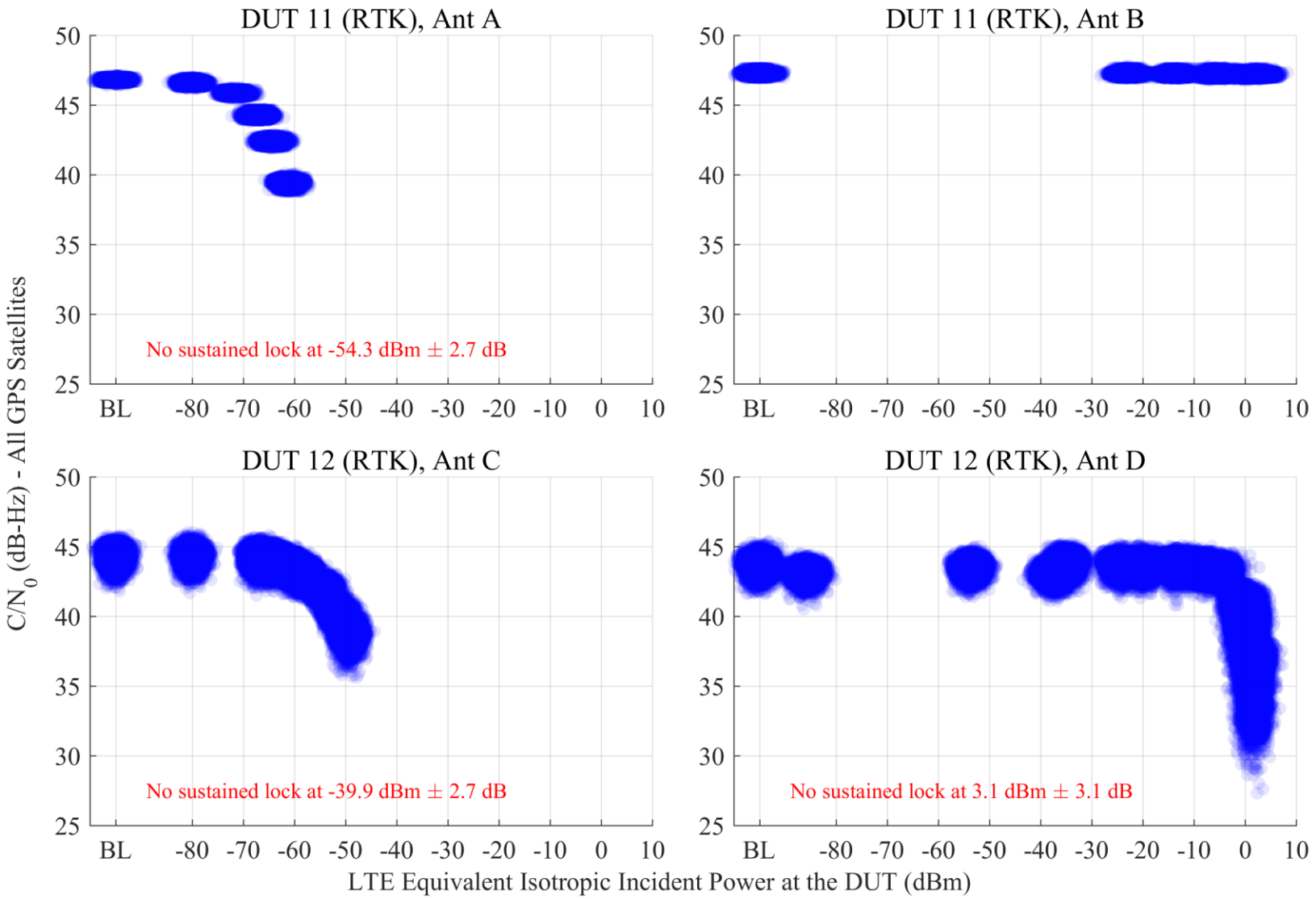

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Fig. 6.49 – pg. 170

Real Time Kinematic

- 3D position error scatter plots
- Downlink
- Nominal satellite condition

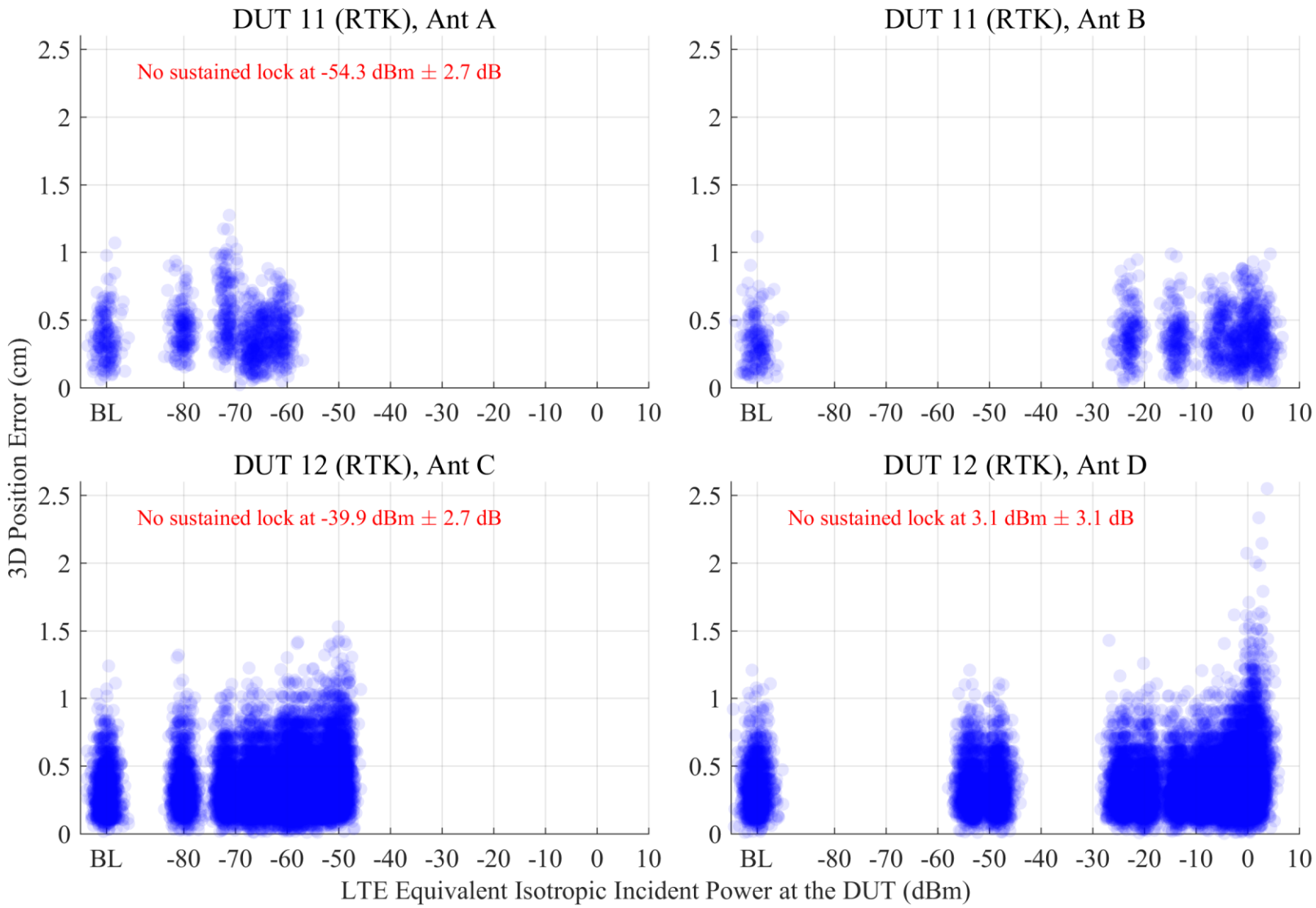

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Fig. 6.51 – pg. 172

Real Time Kinematic

- 95% confidence regions for median C/N_0
- Downlink
- Nominal satellite condition

Baseline (BL) – No LTE Power

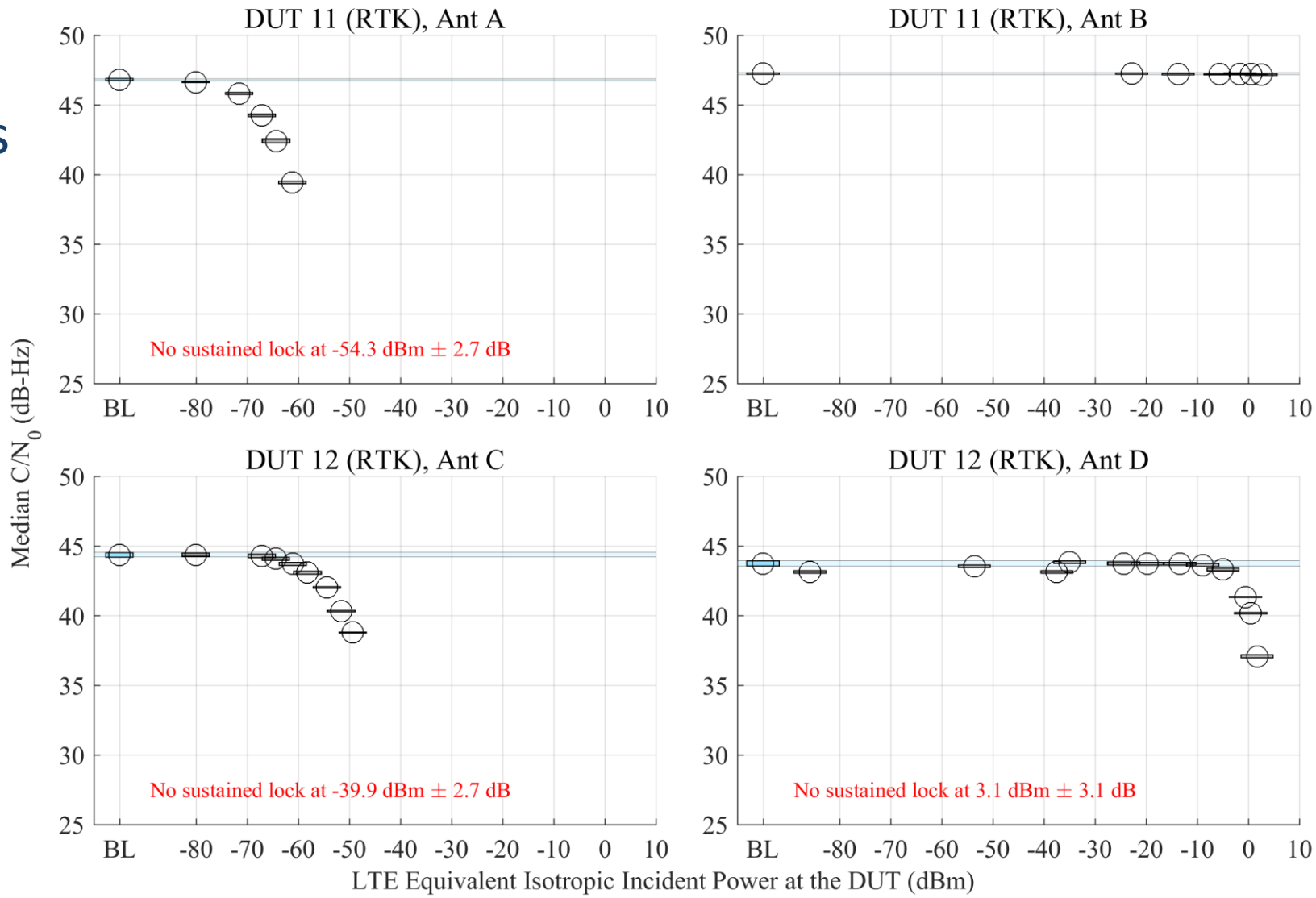

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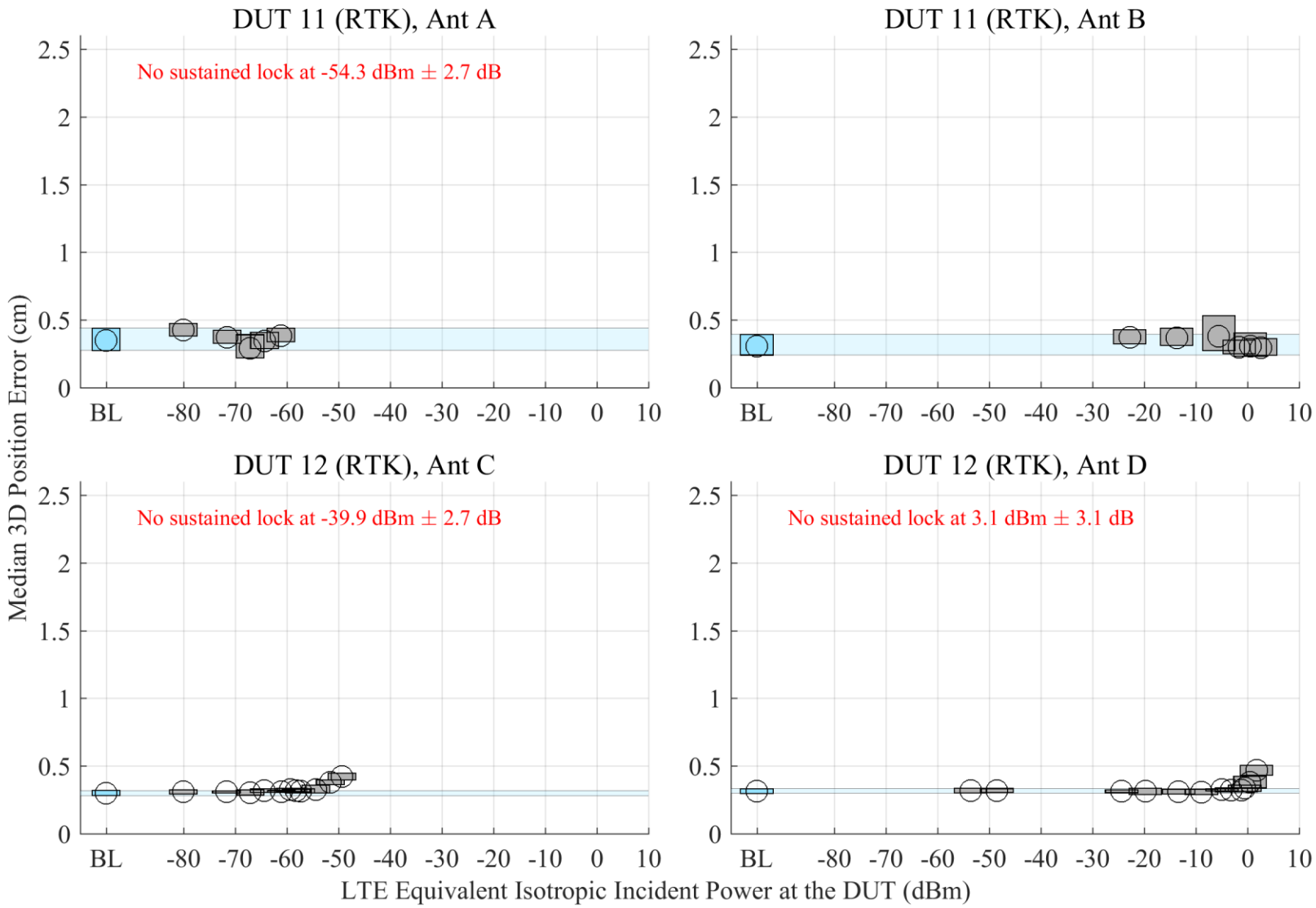
Fig. 6.50 – pg. 171

Real Time Kinematic

- 95% confidence regions for median 3D position error
- Downlink
- Nominal satellite condition

Baseline (BL) – No LTE Power



NASCTN
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Fig. 6.52 – pg. 173

Real Time Kinematic

- Number of reported satellites in view scatter plot
- Downlink
- Nominal satellite condition

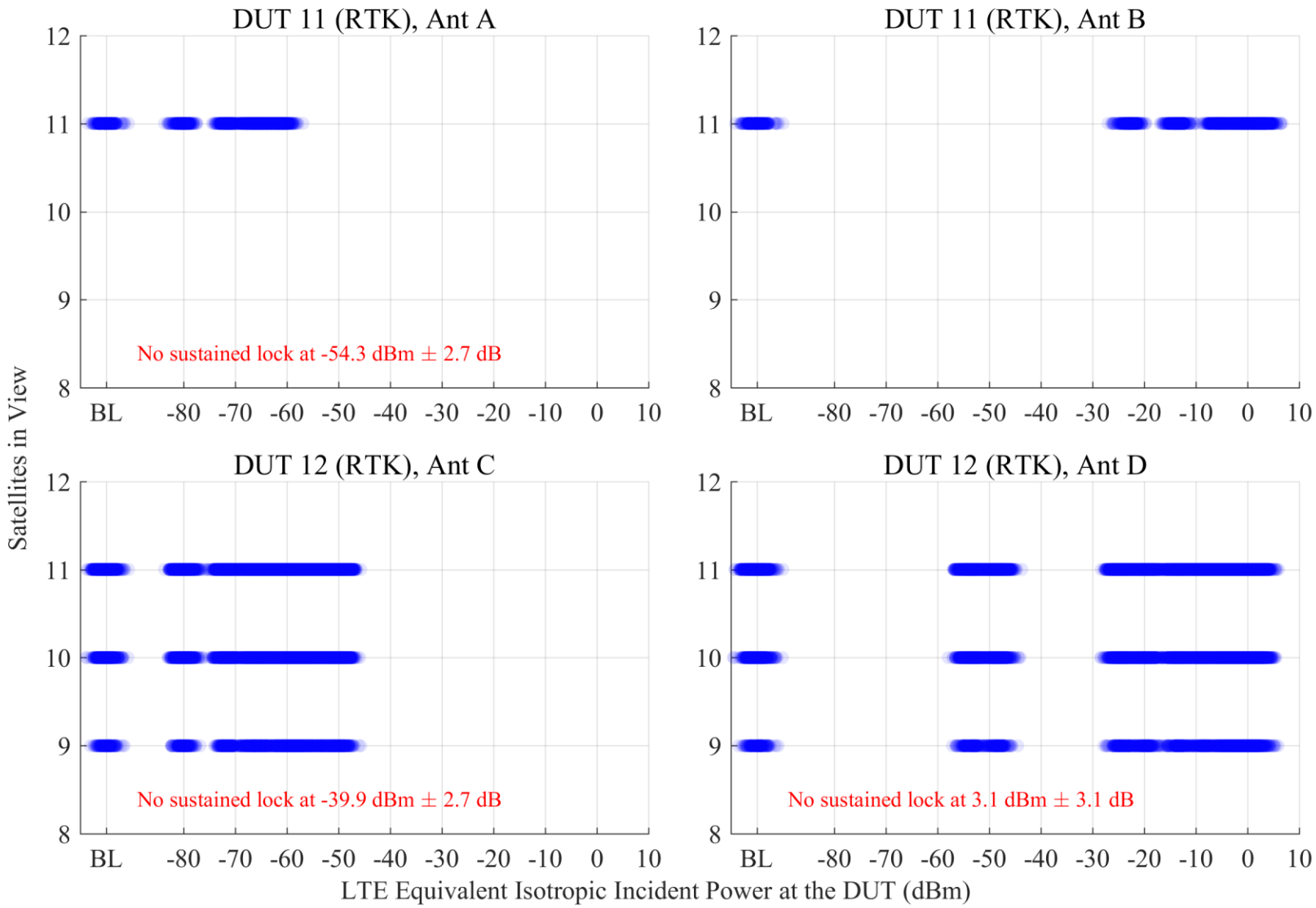

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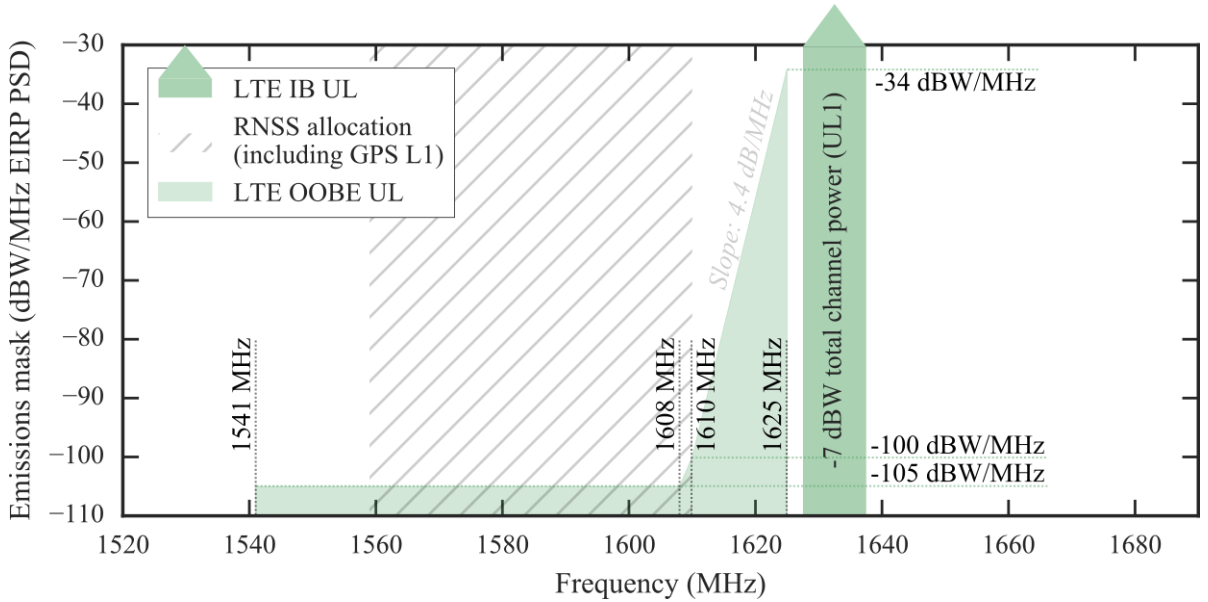
Fig. 6.53 – pg. 174

Real Time Kinematic

- Nominal Satellite Condition
  - Downlink
  - **Uplink 1**
  - Uplink 2
  - Combo DL + UL1



Real Time Kinematic

- C/N0 scatter plots
- Uplink 1
- Nominal satellite condition
- 1200 points per LTE power level per satellite

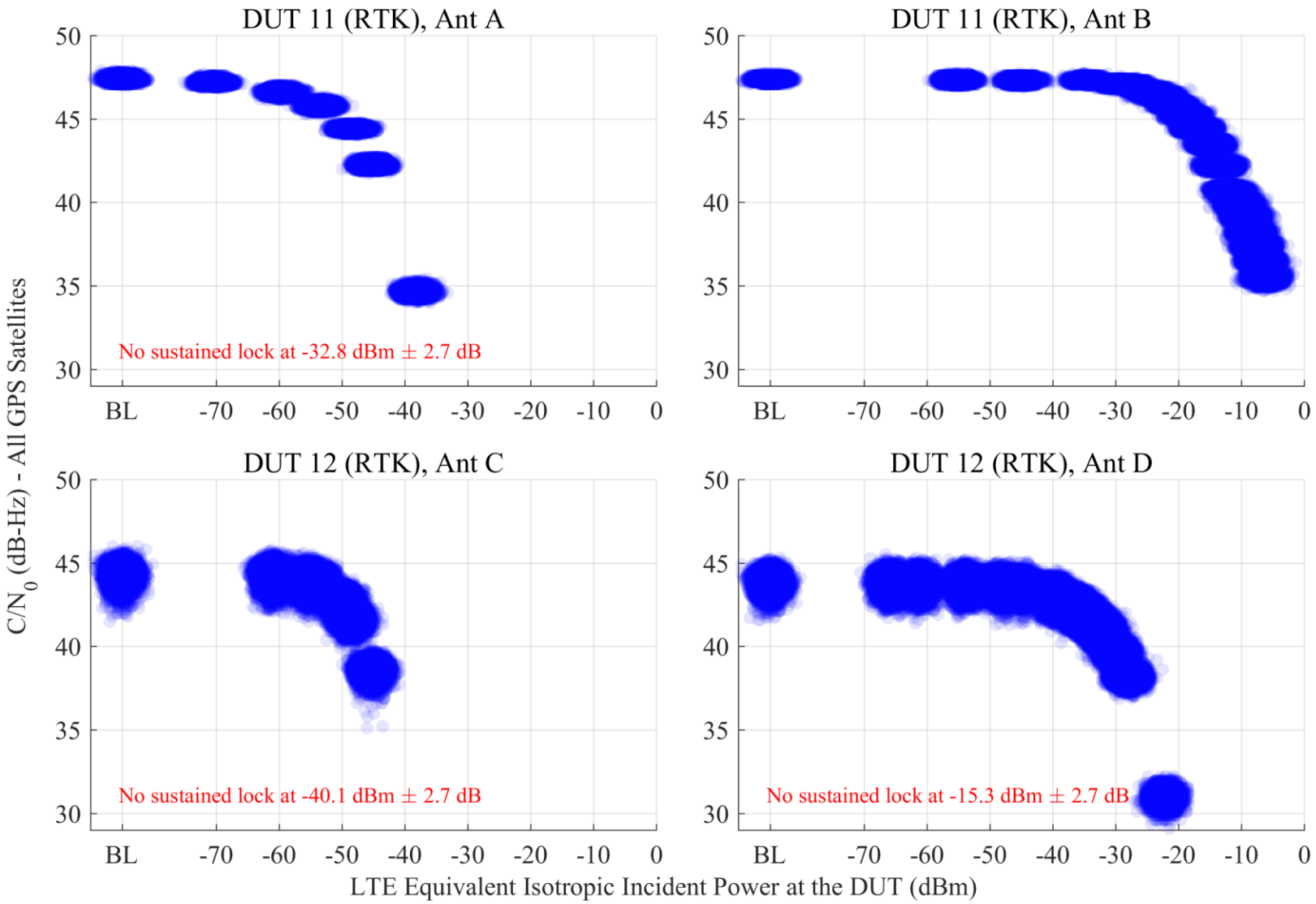


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Fig. 6.54 – pg. 175

Real Time Kinematic

- 3D position error scatter plots
- Uplink 1
- Nominal satellite condition

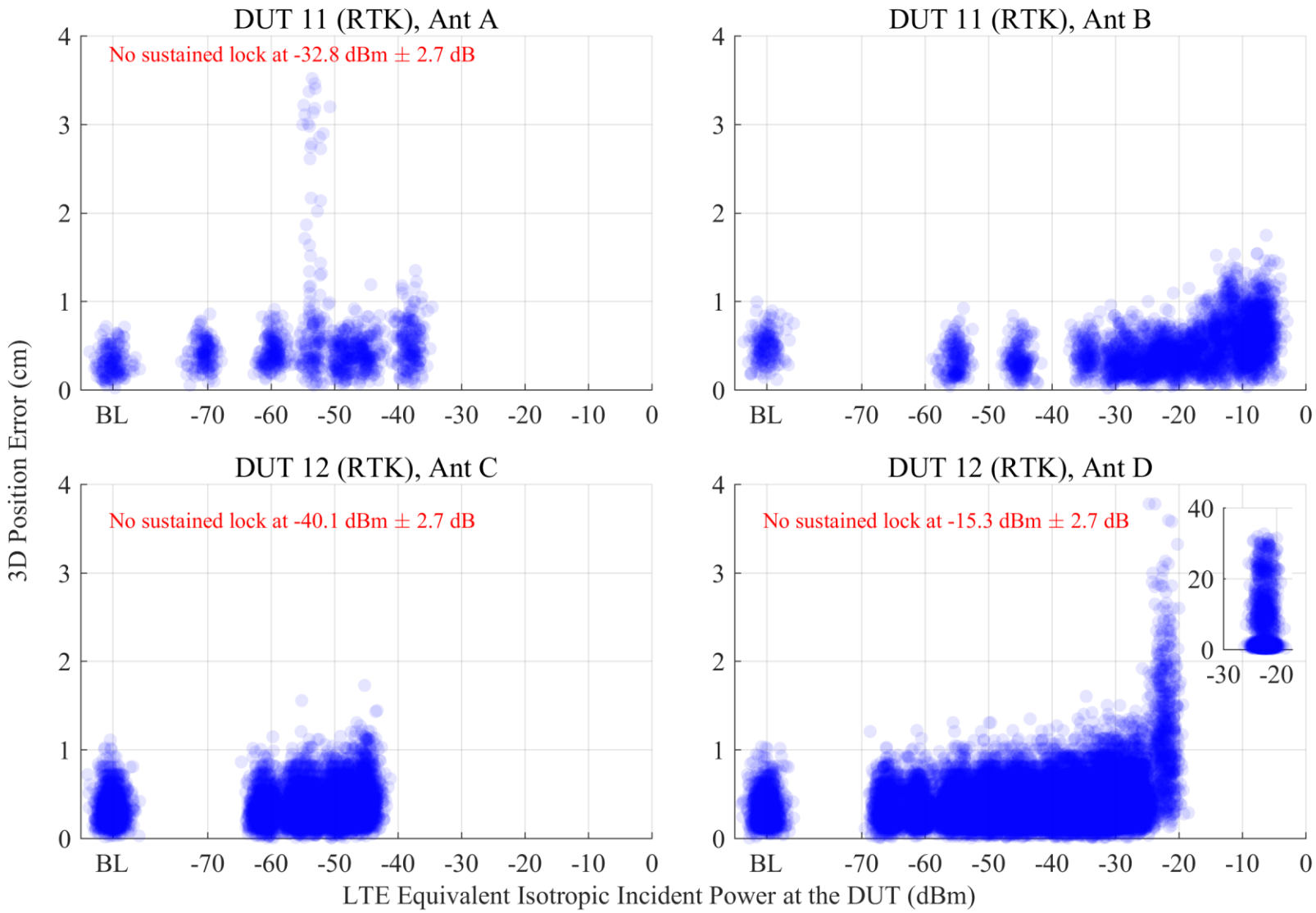

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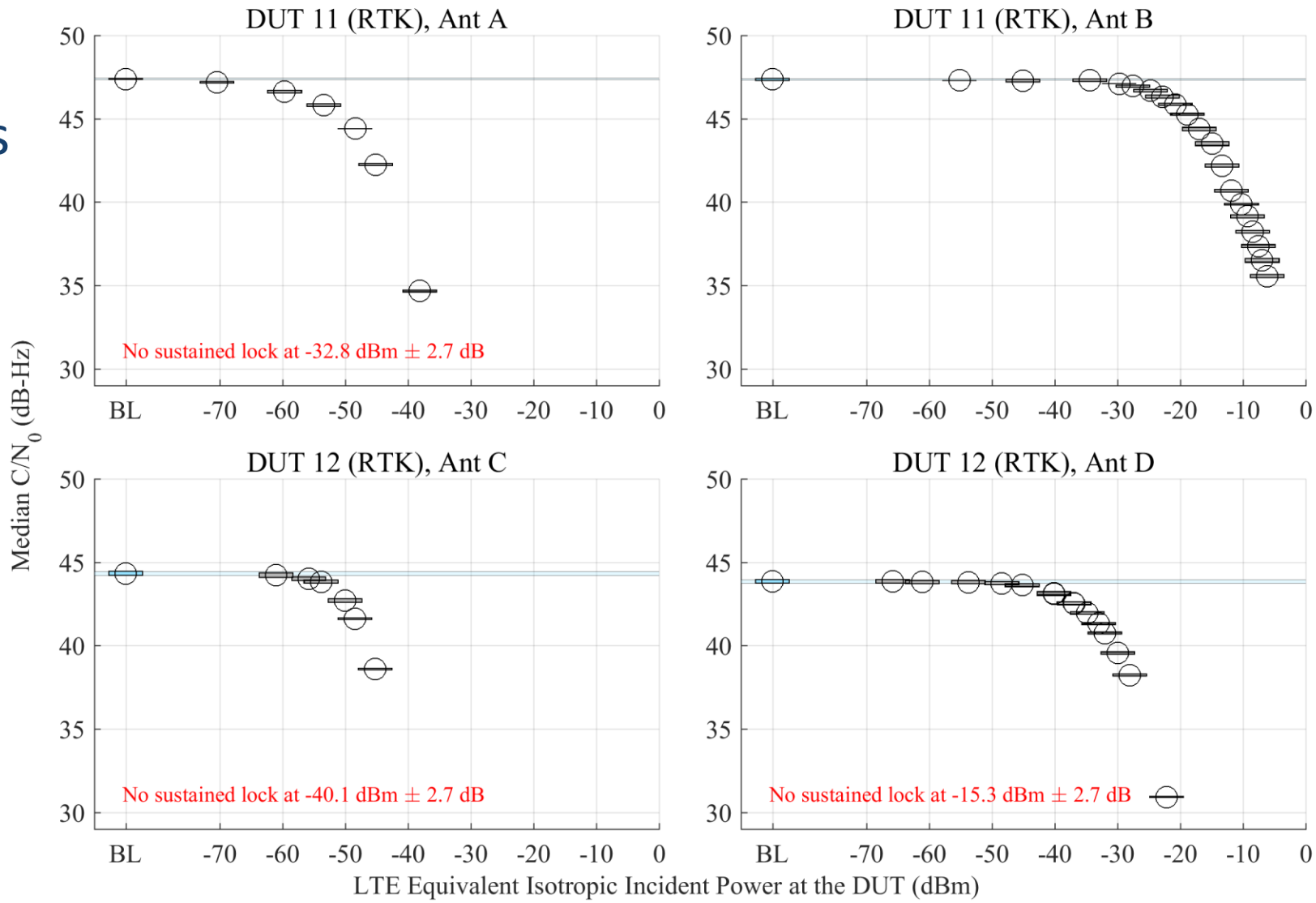
Fig. 6.56 – pg. 177

Real Time Kinematic

- 95% confidence regions for median C/N_0
- Uplink 1
- Nominal satellite condition

Baseline (BL) – No LTE Power



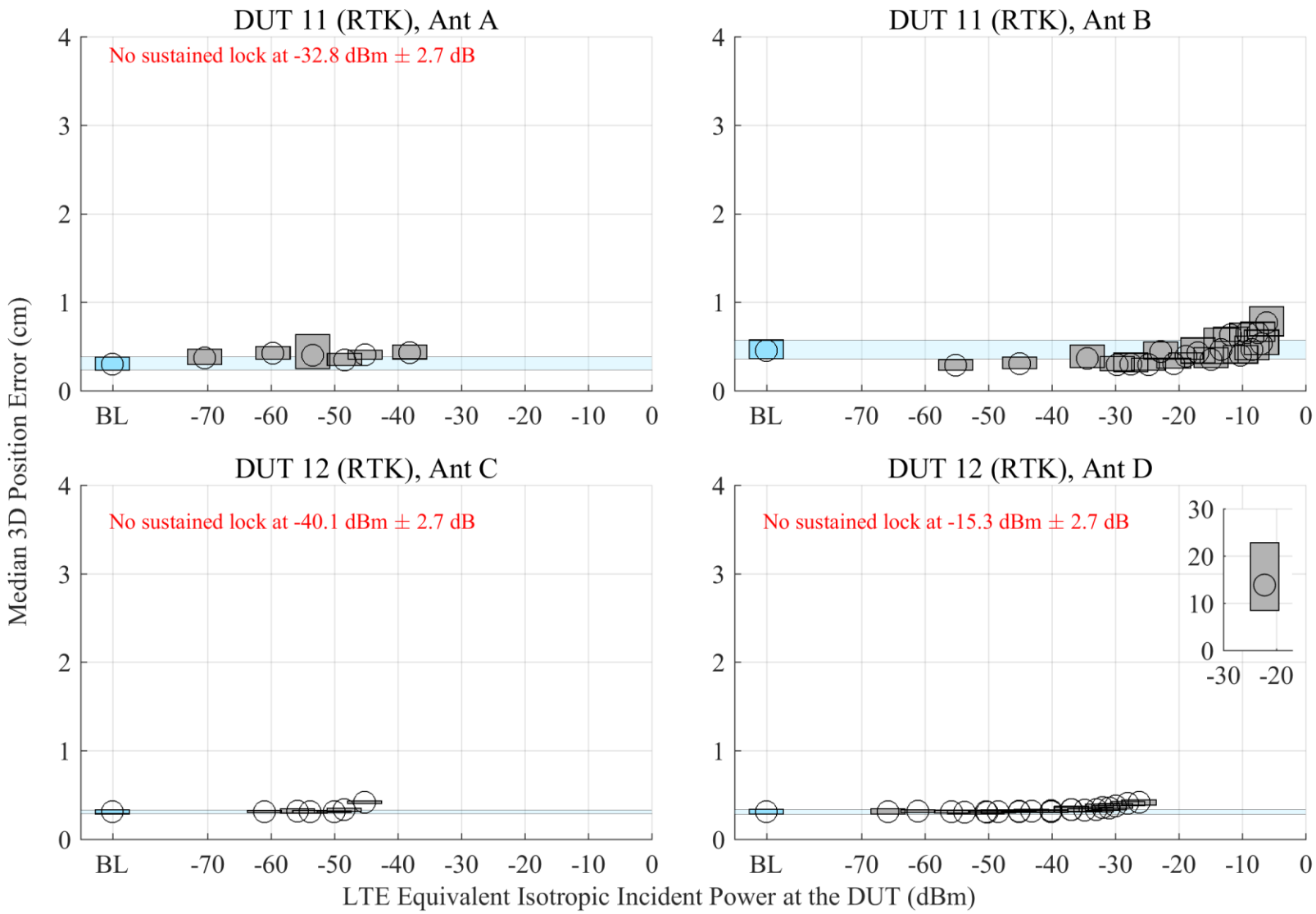
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.55 – pg. 176

Real Time Kinematic

- 95% confidence regions for median 3D position error
- Uplink 1
- Nominal satellite condition

Baseline (BL) – No LTE Power



NASCTN
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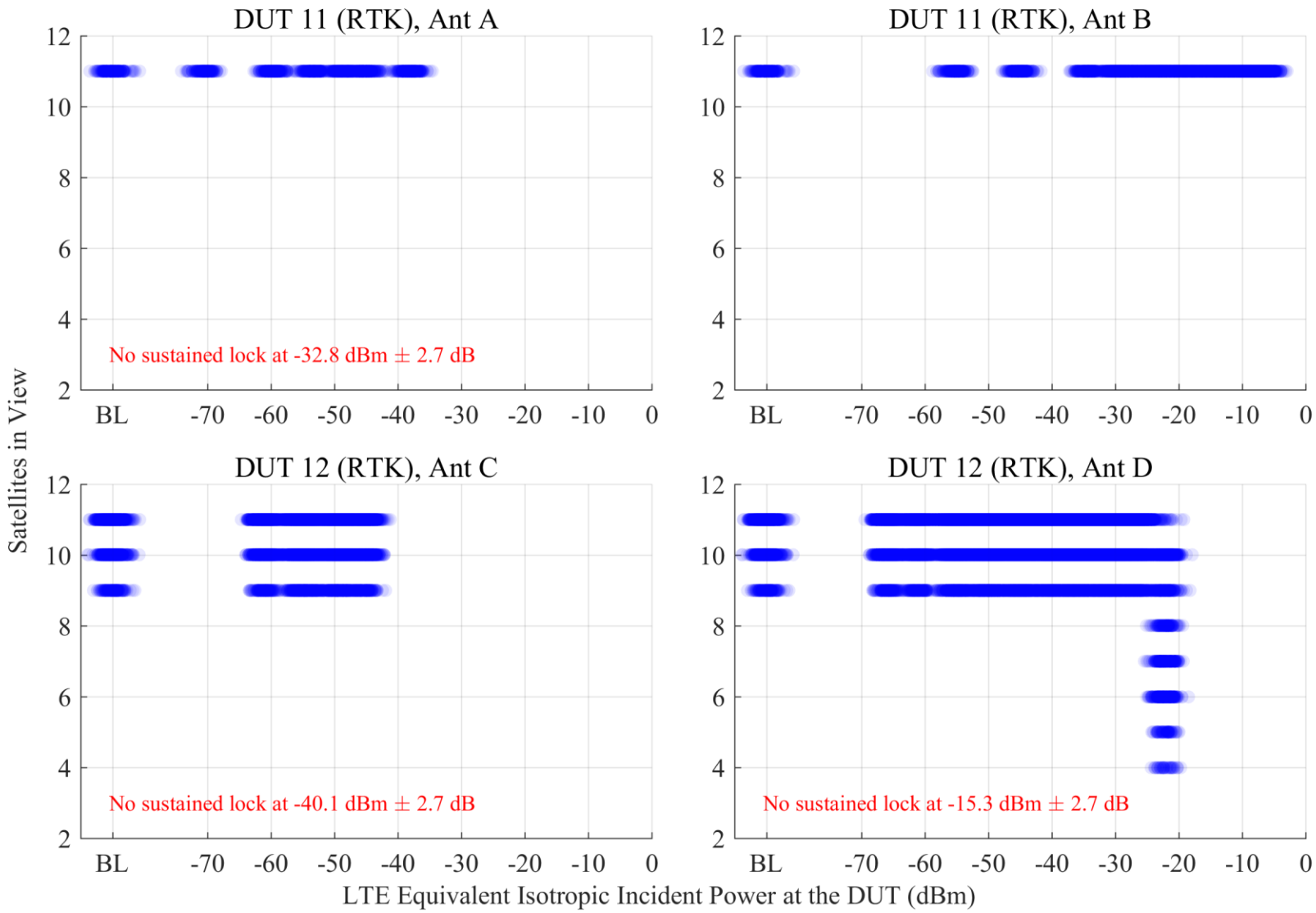
Fig. 6.57 – pg. 178

Real Time Kinematic

- Number of reported satellites in view scatter plot
- Uplink 1
- Nominal satellite condition



NASCTN
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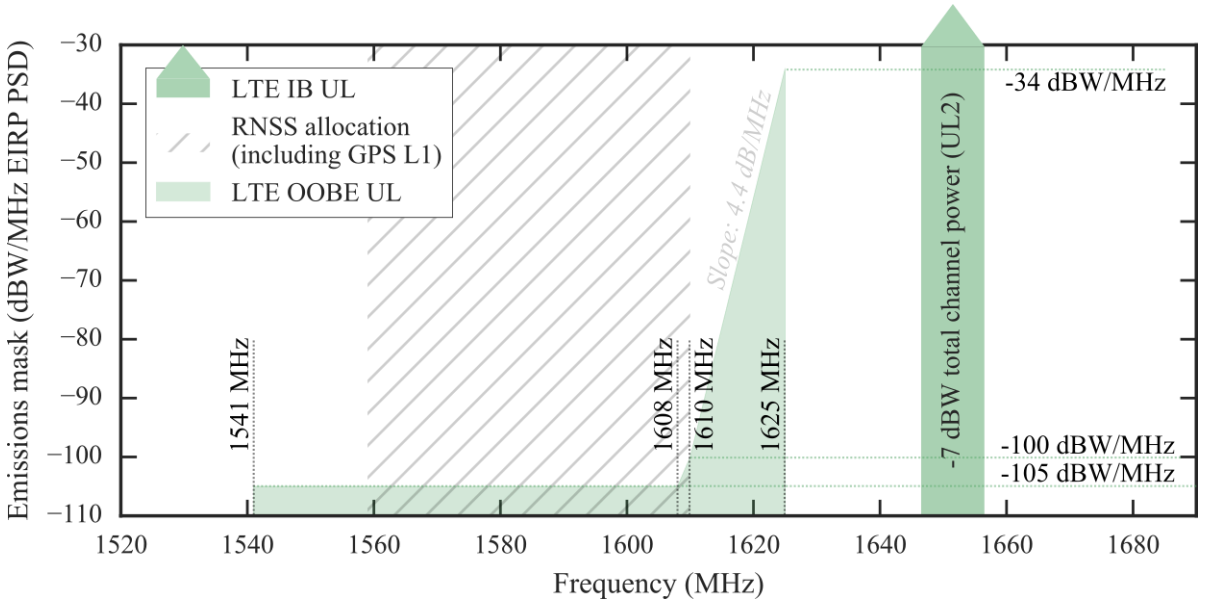
Fig. 6.58 – pg. 179

Real Time Kinematic

- Nominal Satellite Condition
  - Downlink
  - Uplink 1
  - **Uplink 2**
  - Combo DL + UL1



Real Time Kinematic

- C/N0 scatter plots
- Uplink 2
- Nominal satellite condition
- 1200 points per LTE power level per satellite

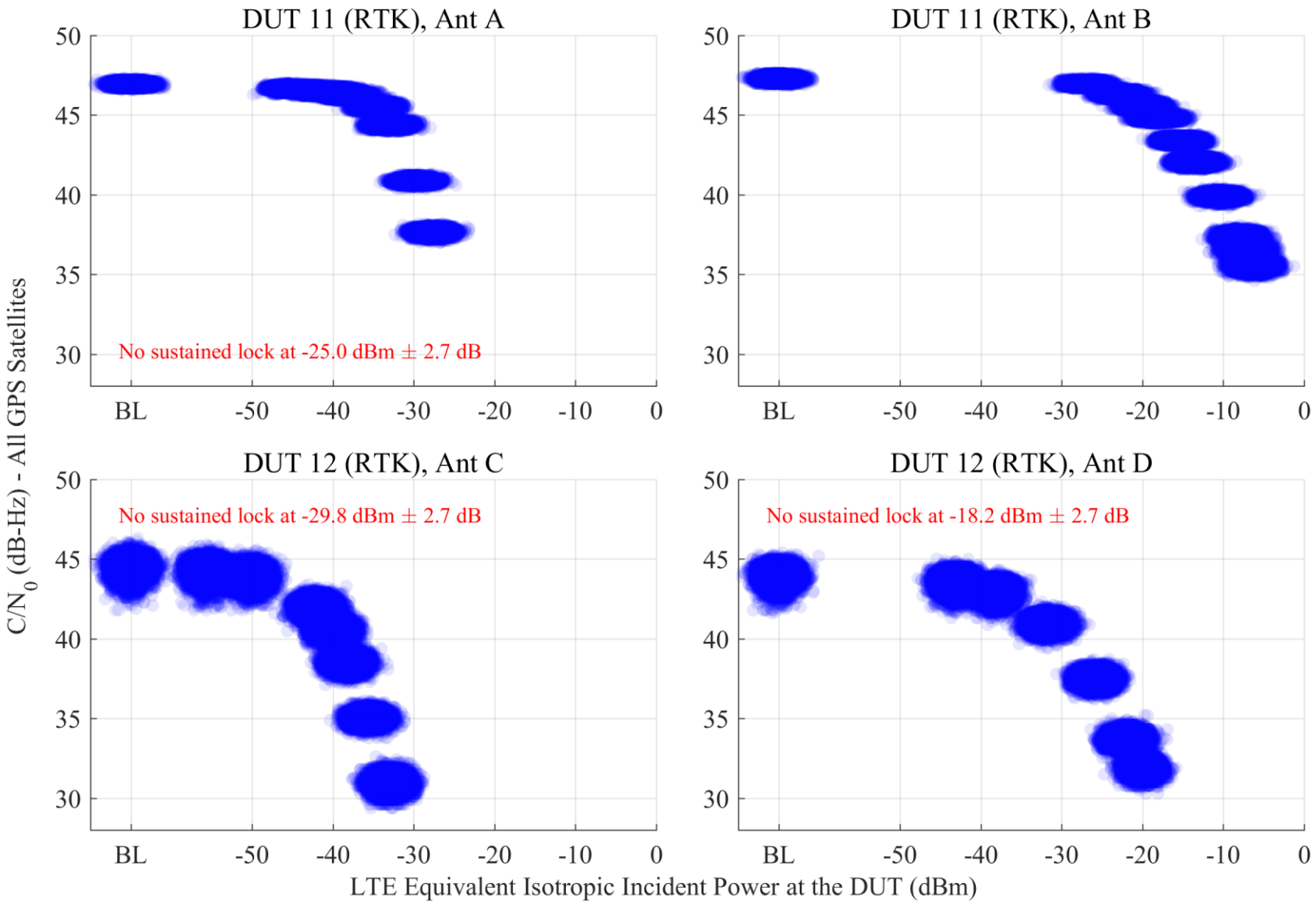


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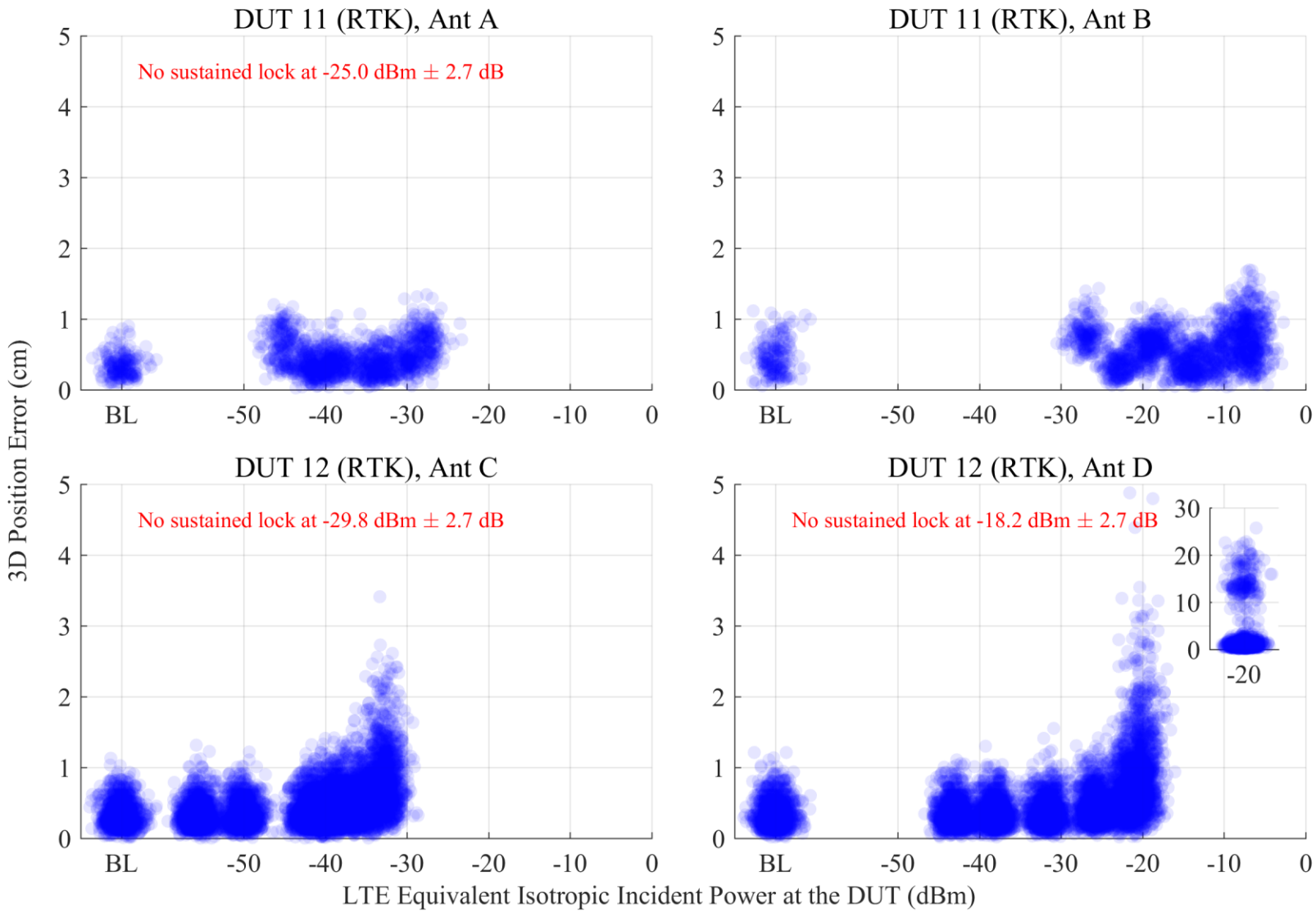
Fig. 6.59 – pg. 180

Real Time Kinematic

- 3D position error scatter plots
- Uplink 2
- Nominal satellite condition



NASCTN
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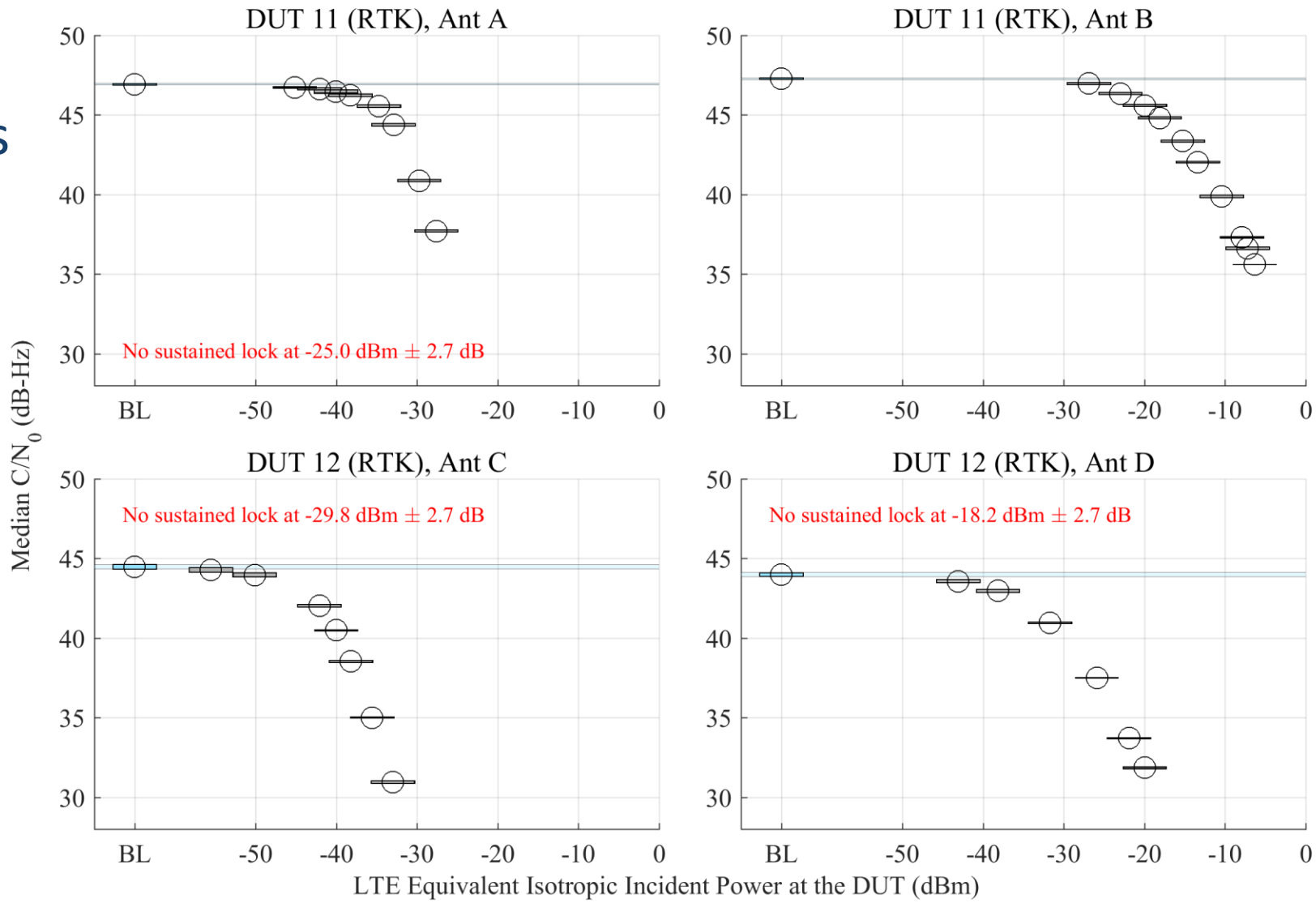
Fig. 6.61 – pg. 182

Real Time Kinematic

- 95% confidence regions for median C/N_0
- Uplink 2
- Nominal satellite condition

Baseline (BL) – No LTE Power



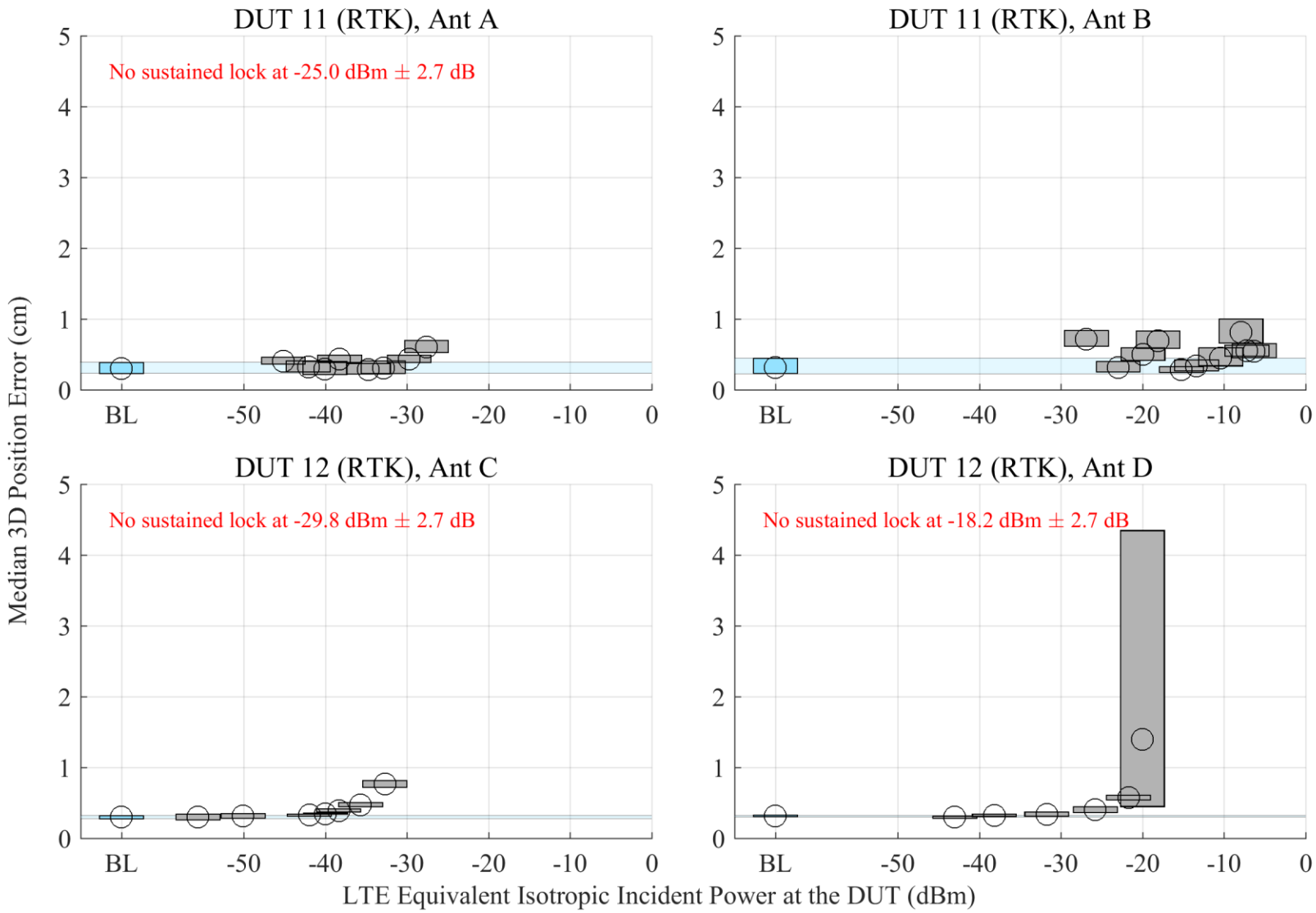
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.60 – pg. 181

Real Time Kinematic

- 95% confidence regions for median 3D position error
- Uplink 2
- Nominal satellite condition

Baseline (BL) – No LTE Power

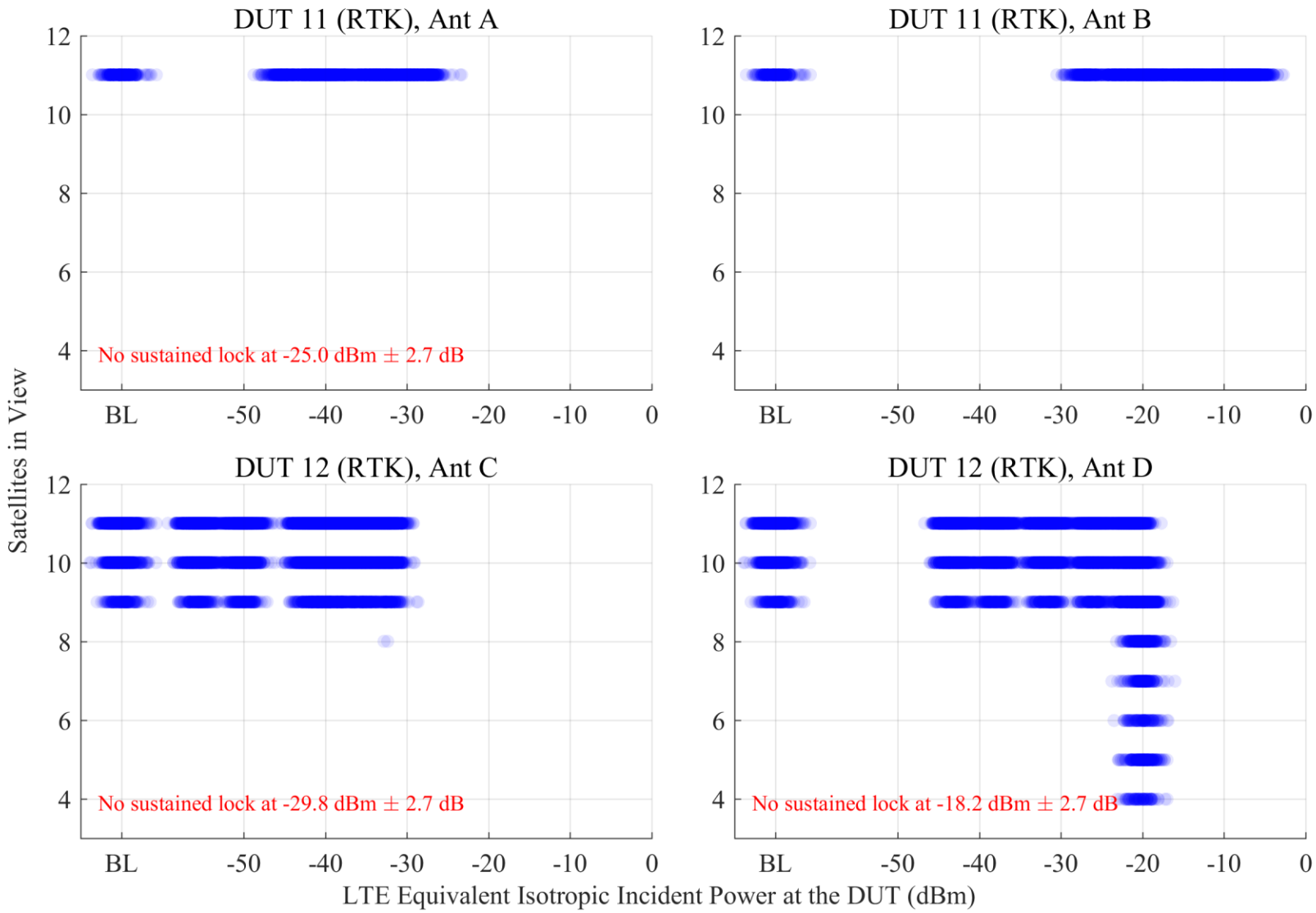


NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.62 – pg. 183

Real Time Kinematic

- Number of reported satellites in view scatter plot
- Uplink 2
- Nominal satellite condition

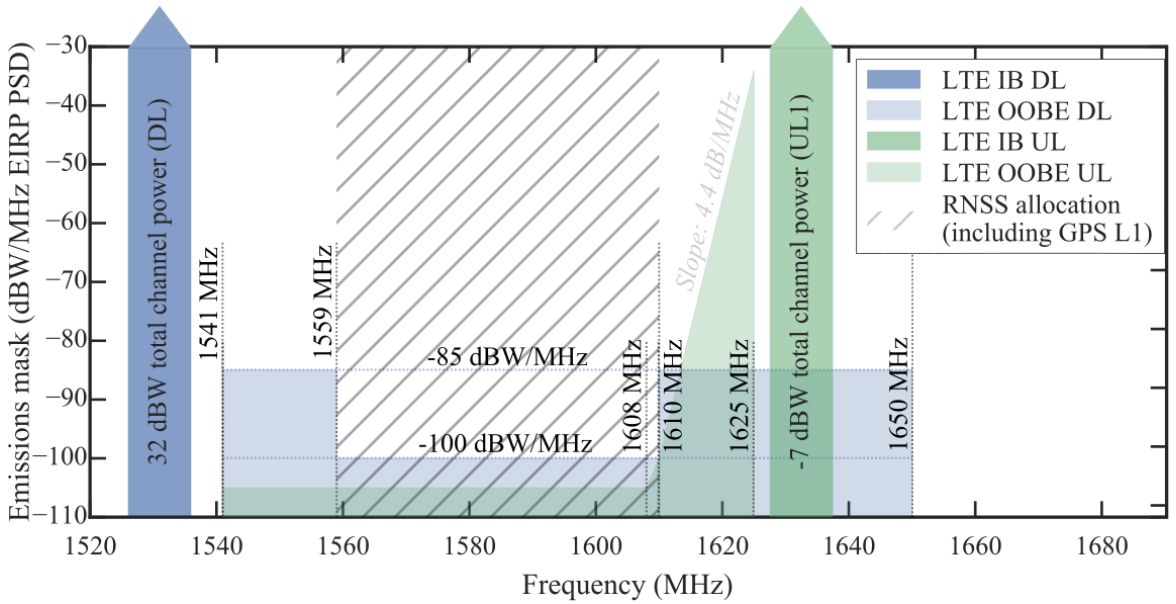


NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.63 – pg. 184

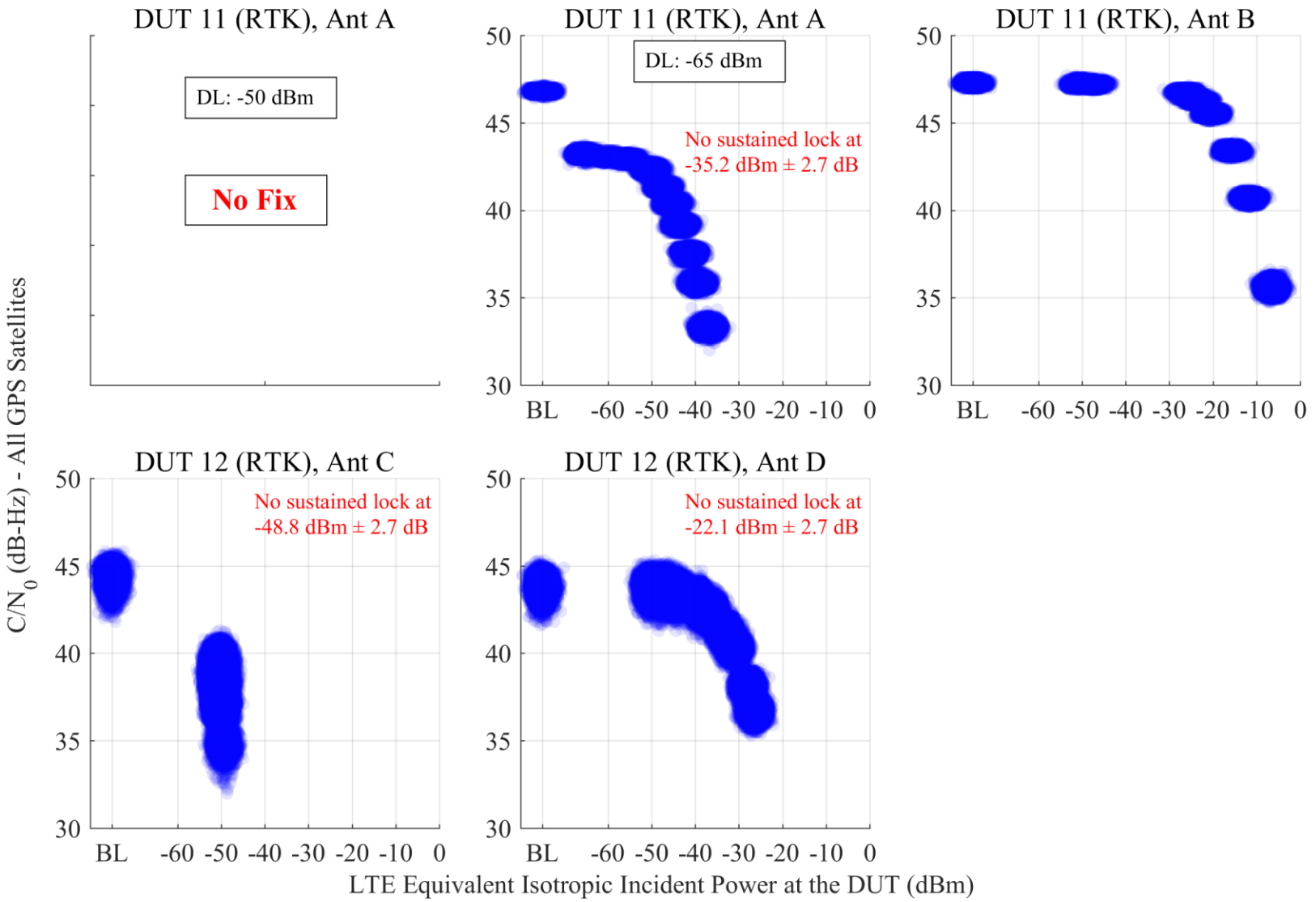
Real Time Kinematic

- Nominal Satellite Condition
  - Downlink
  - Uplink 1
  - Uplink 2
  - **Combo DL + UL1**



Real Time Kinematic

- C/N0 scatter plots
- Combo DL + UL1
- Nominal satellite condition
- 1200 points per LTE power level per satellite
- DL fixed: -50 dBm
- Low-Level DL: -65 dBm



NASCTN
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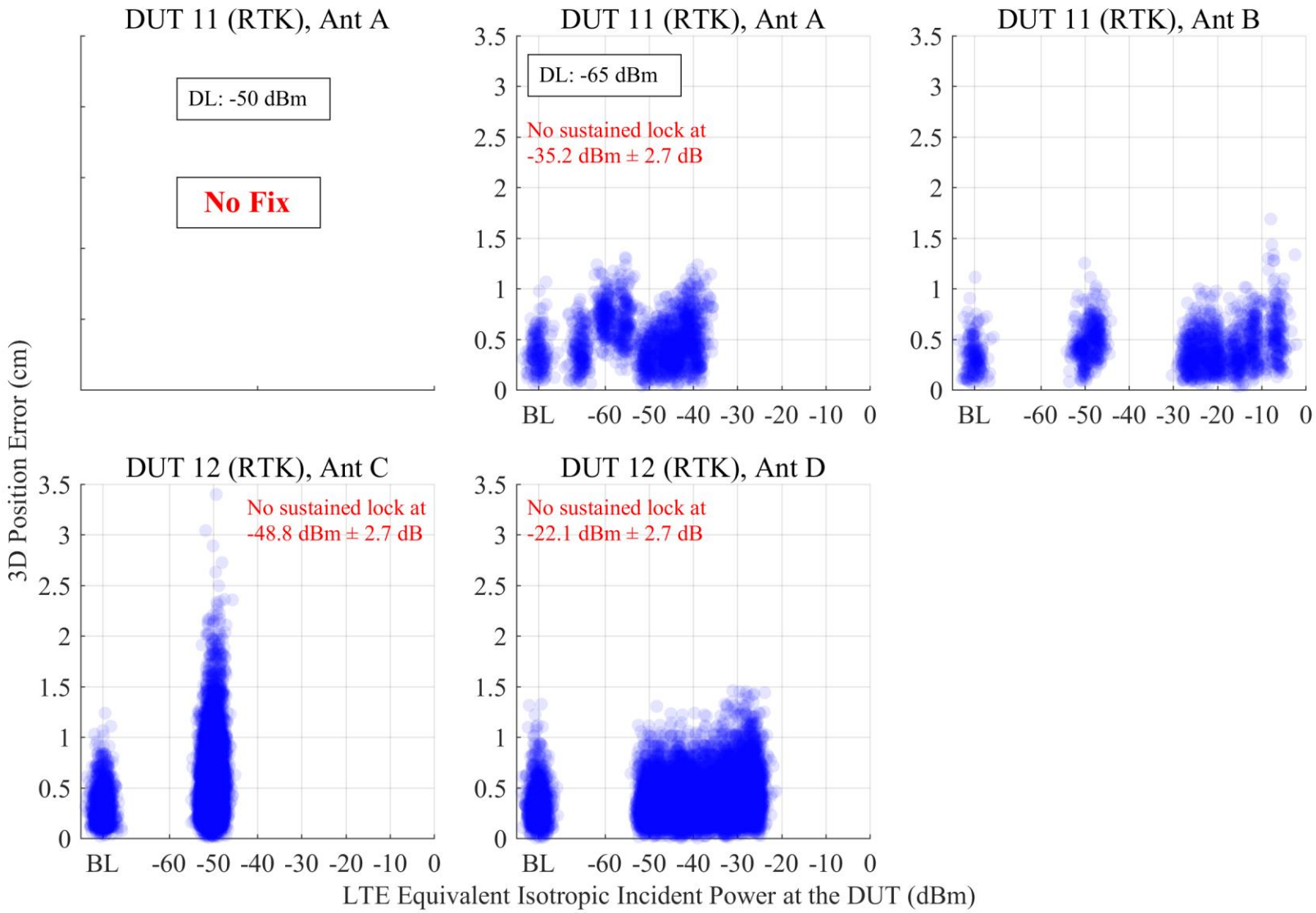
Fig. 6.64 – pg. 185

Real Time Kinematic

- 3D position error scatter plots
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm
- Low-Level DL: -65 dBm



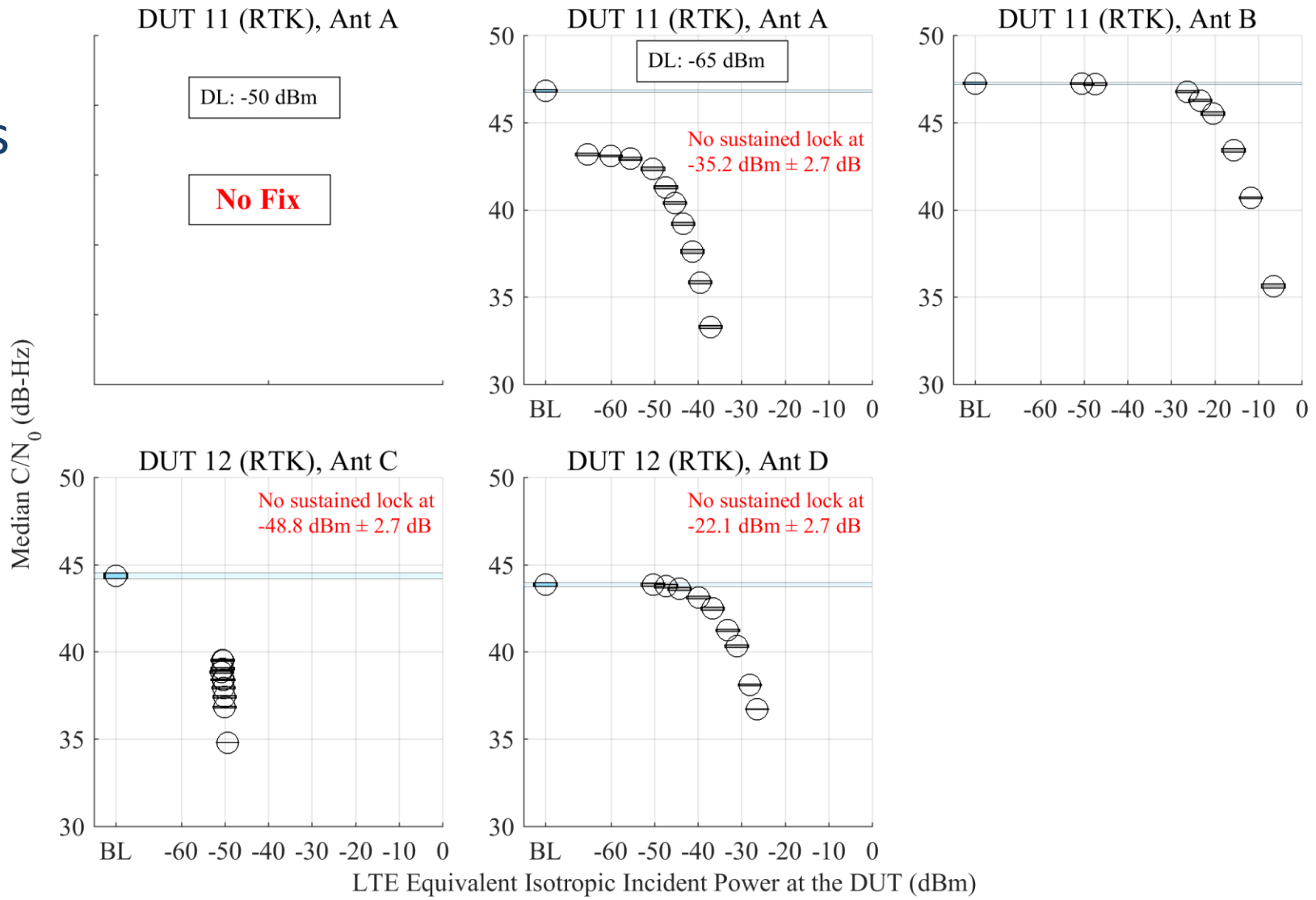
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.66 – pg. 187

Real Time Kinematic

- 95% confidence regions for median C/N_0
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm
- Low-Level DL: -65 dBm

Baseline (BL) – No LTE Power



NASCTN
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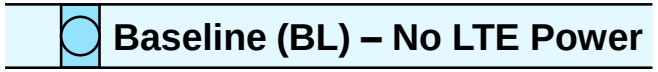
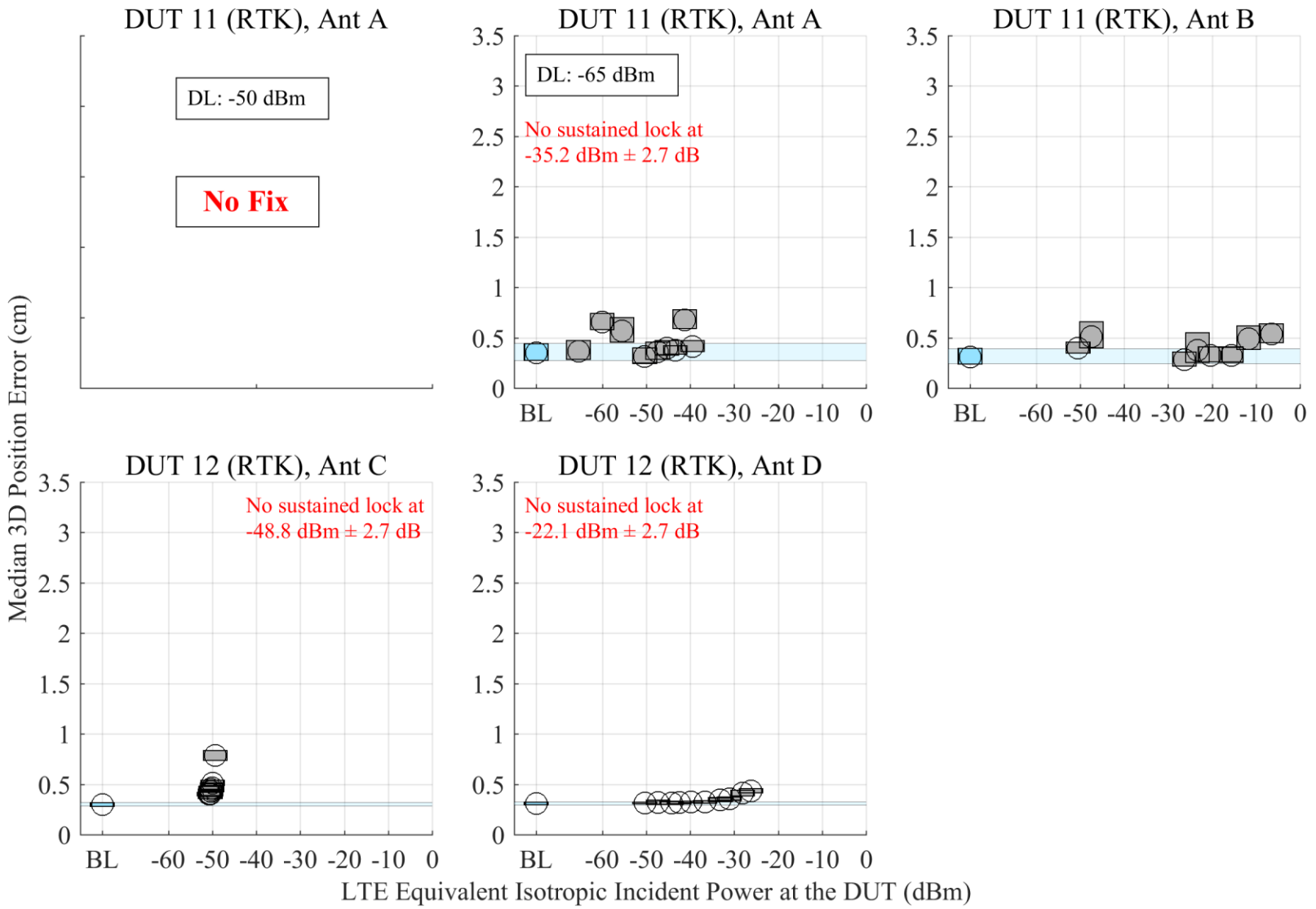
Fig. 6.65 – pg. 186

Real Time Kinematic

- 95% confidence regions for median 3D position error
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm
- Low-Level DL: -65 dBm





NASCTN
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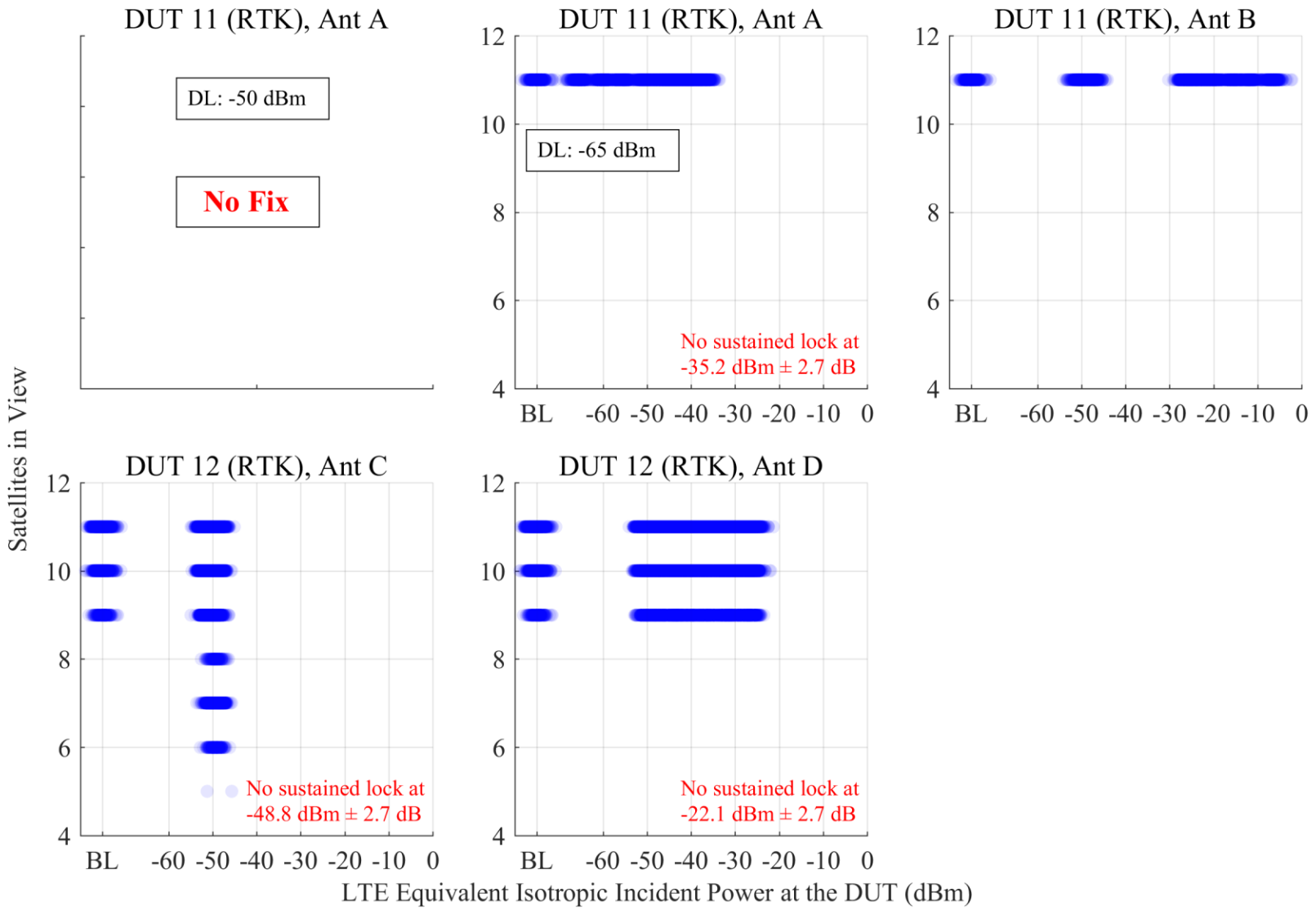
Fig. 6.67 – pg. 188

Real Time Kinematic

- Number of reported satellites in view scatter plot
- Combo DL + UL1
- Nominal satellite condition



NASCTN
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Fig. 6.68 – pg. 189

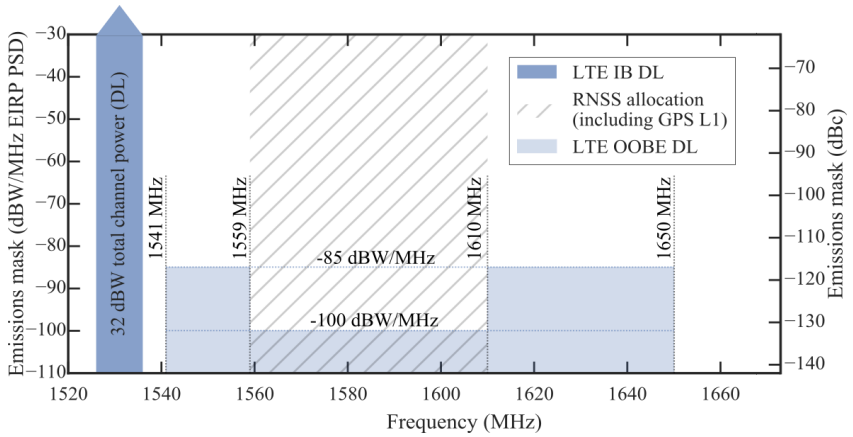
General Location and Navigation

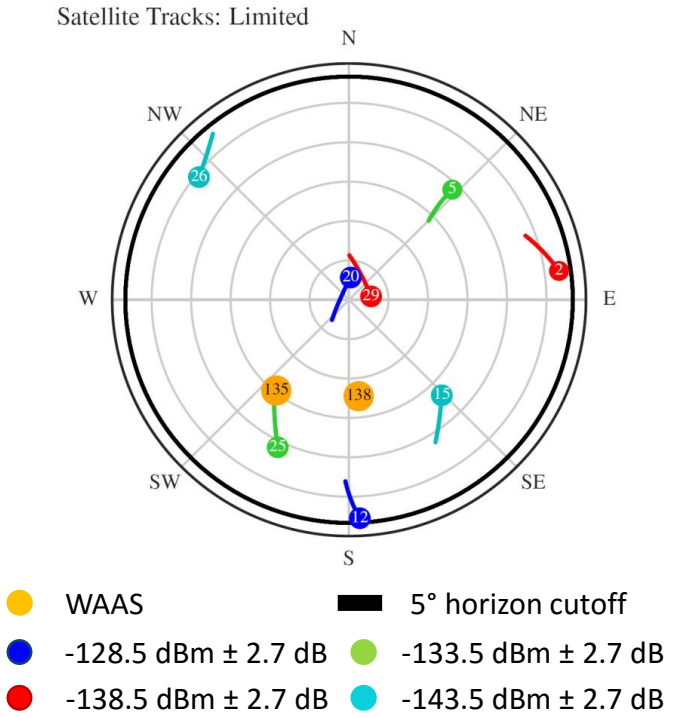
Limited Satellite Constellation

NASCTN
National Advanced Spectrum and Communications Test Network

General Location and Navigation

- Limited Satellite Condition
  - **Downlink**
  - Uplink 1

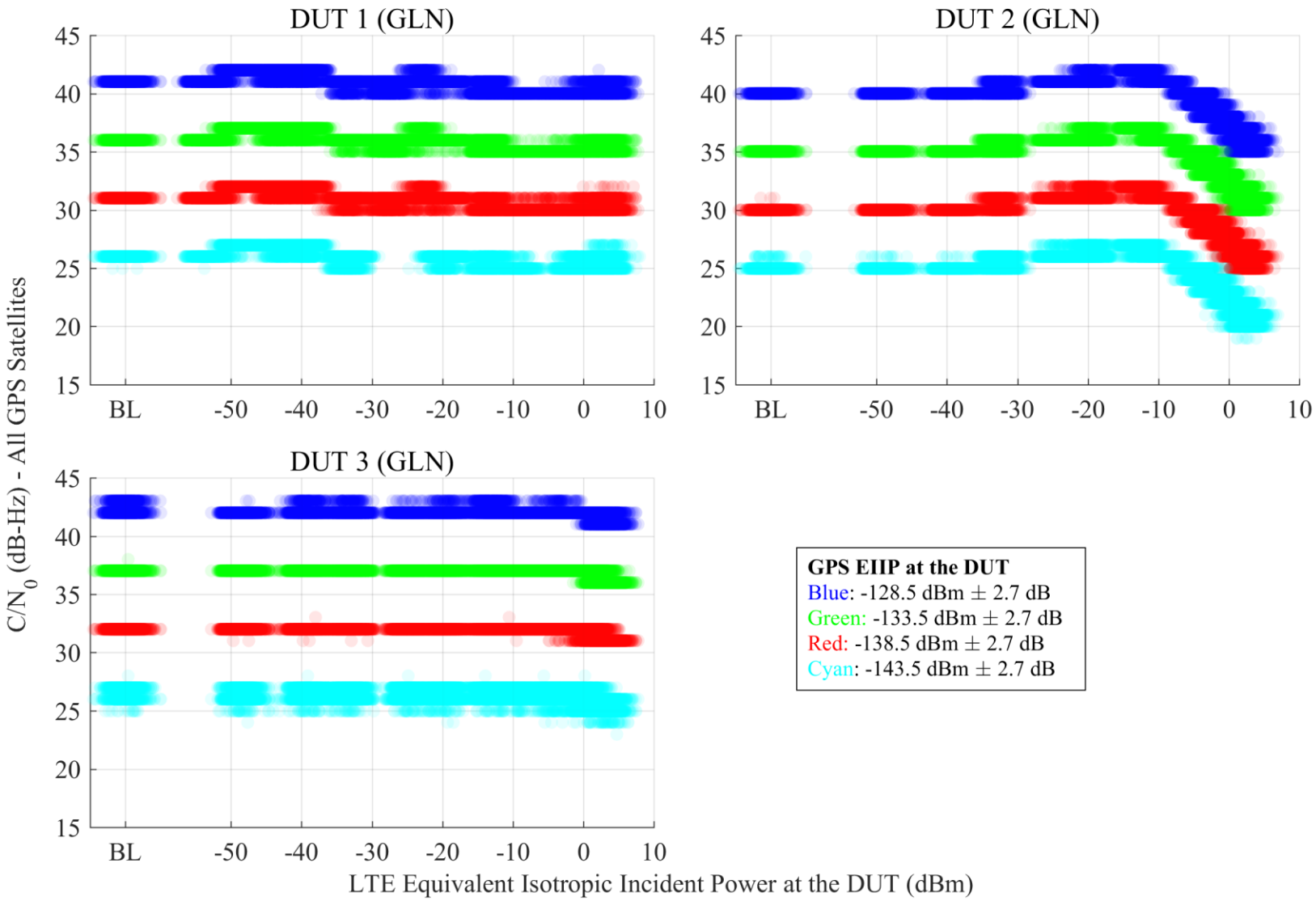




NASCTN
National Advanced Spectrum and Communications Test Network

General Location

- C/N0 scatter plots
- Downlink
- Limited satellite condition
- 600 points per LTE power level per satellite

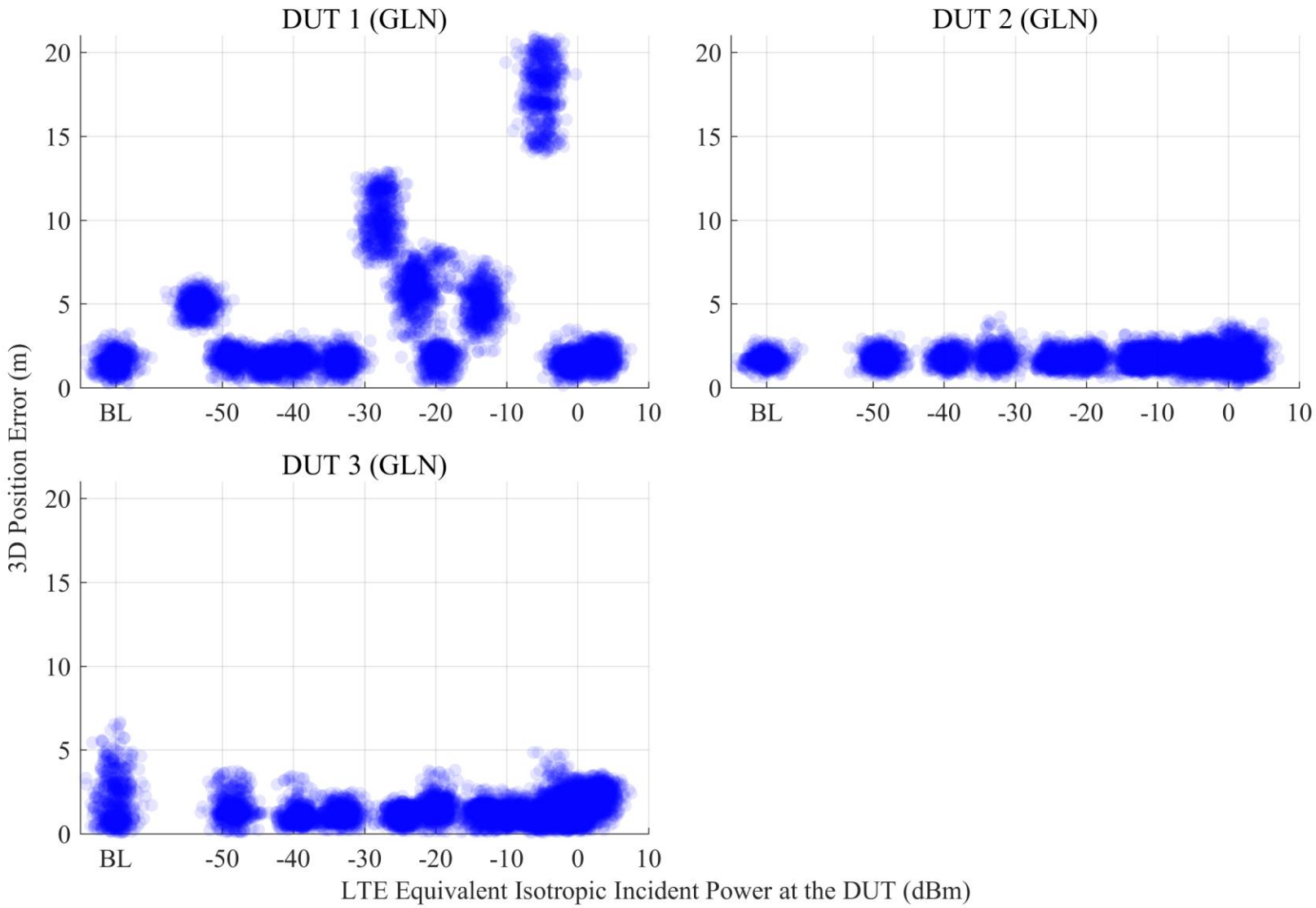


NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.109 – pg. 234

General Location

- 3D position error scatter plots
- Downlink
- Limited satellite condition



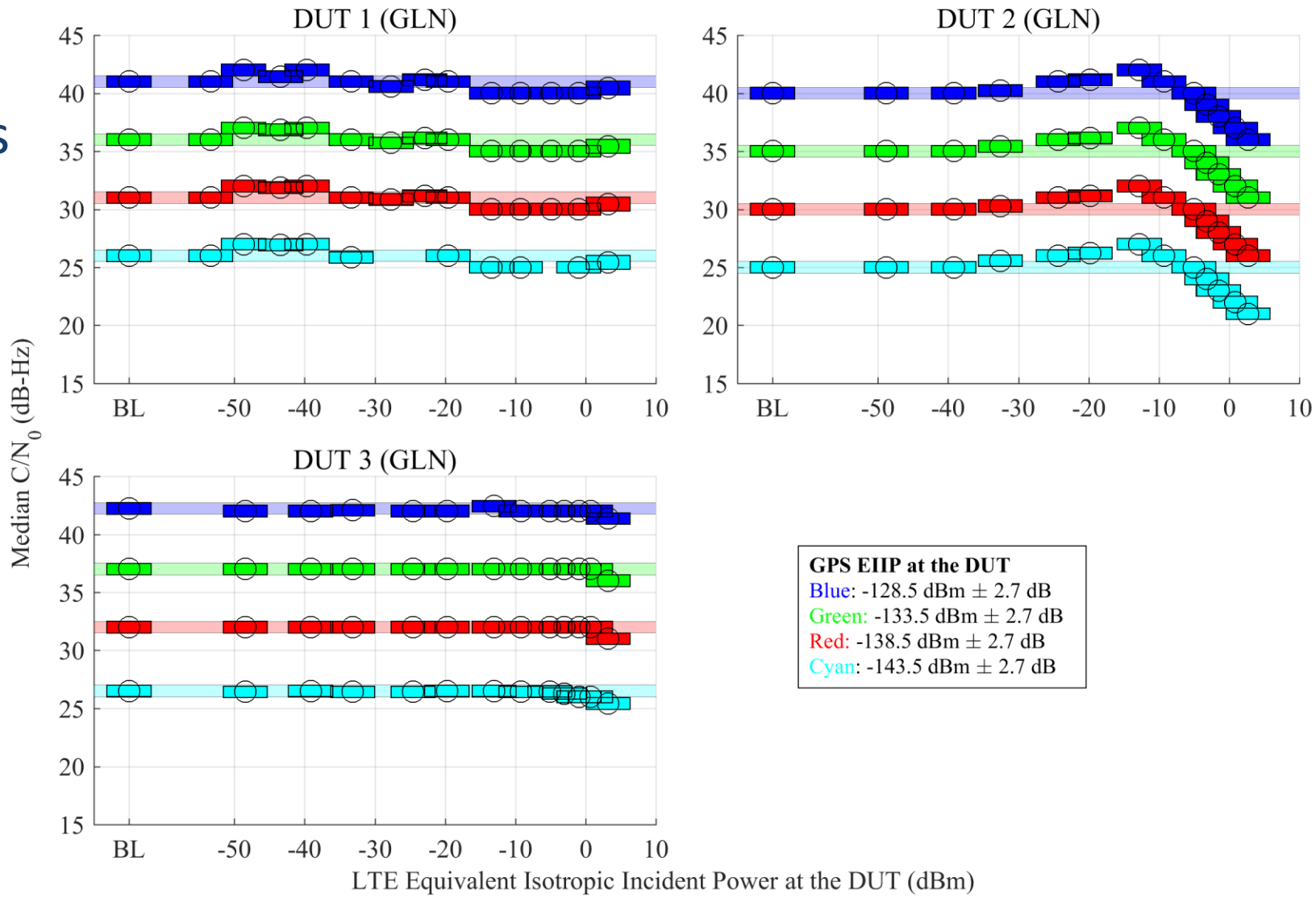
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.111 – pg. 236

General Location

- 95% confidence regions for median C/N_0
- Downlink
- Limited satellite condition

-128.5 dBm	Baseline (BL) – No LTE Power
-133.5 dBm	Baseline (BL) – No LTE Power
-138.5 dBm	Baseline (BL) – No LTE Power
-143.5 dBm	Baseline (BL) – No LTE Power



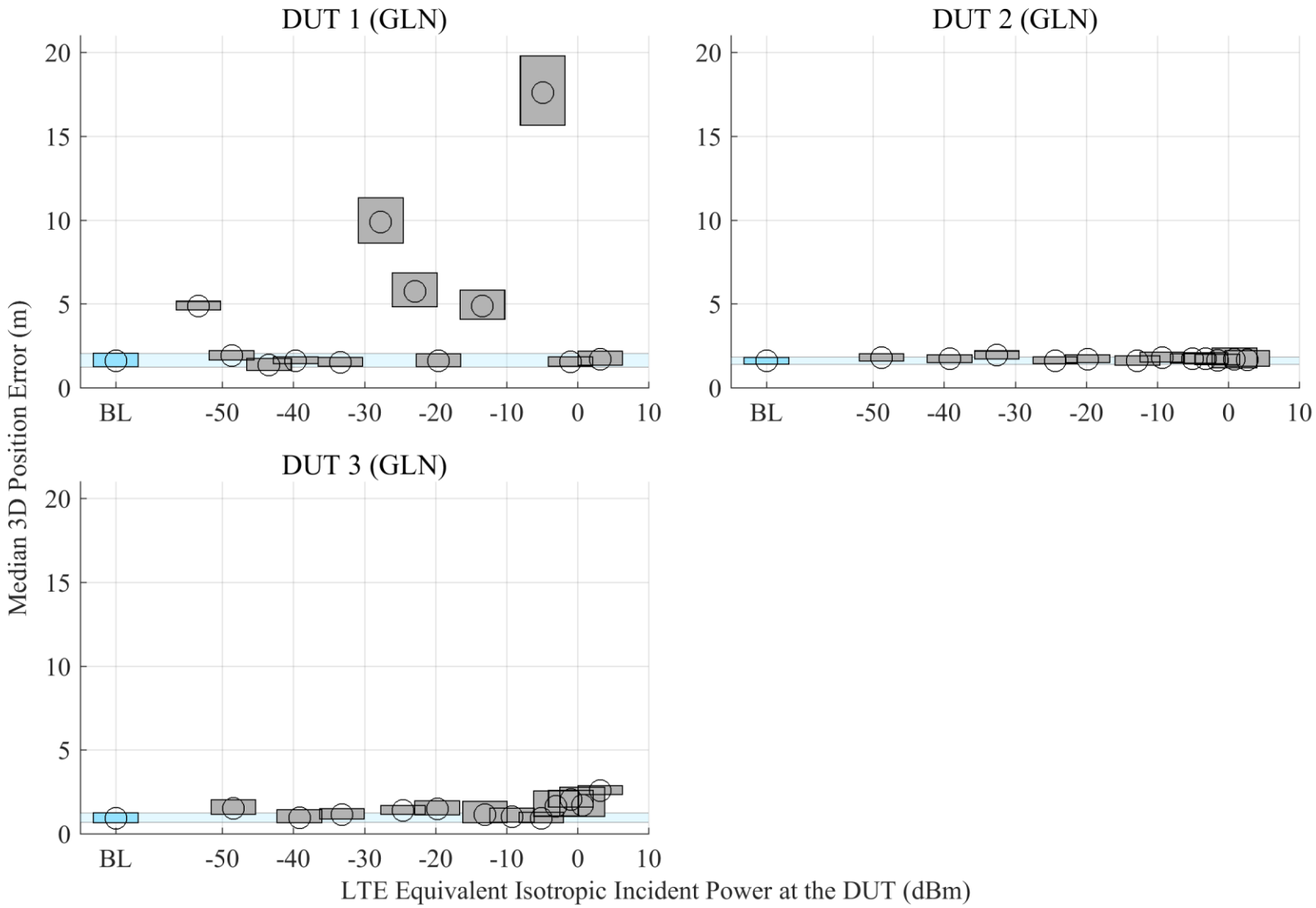
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.110 – pg. 235

General Location

- 95% confidence regions for median 3D position error
- Downlink
- Limited satellite condition

Baseline (BL) – No LTE Power

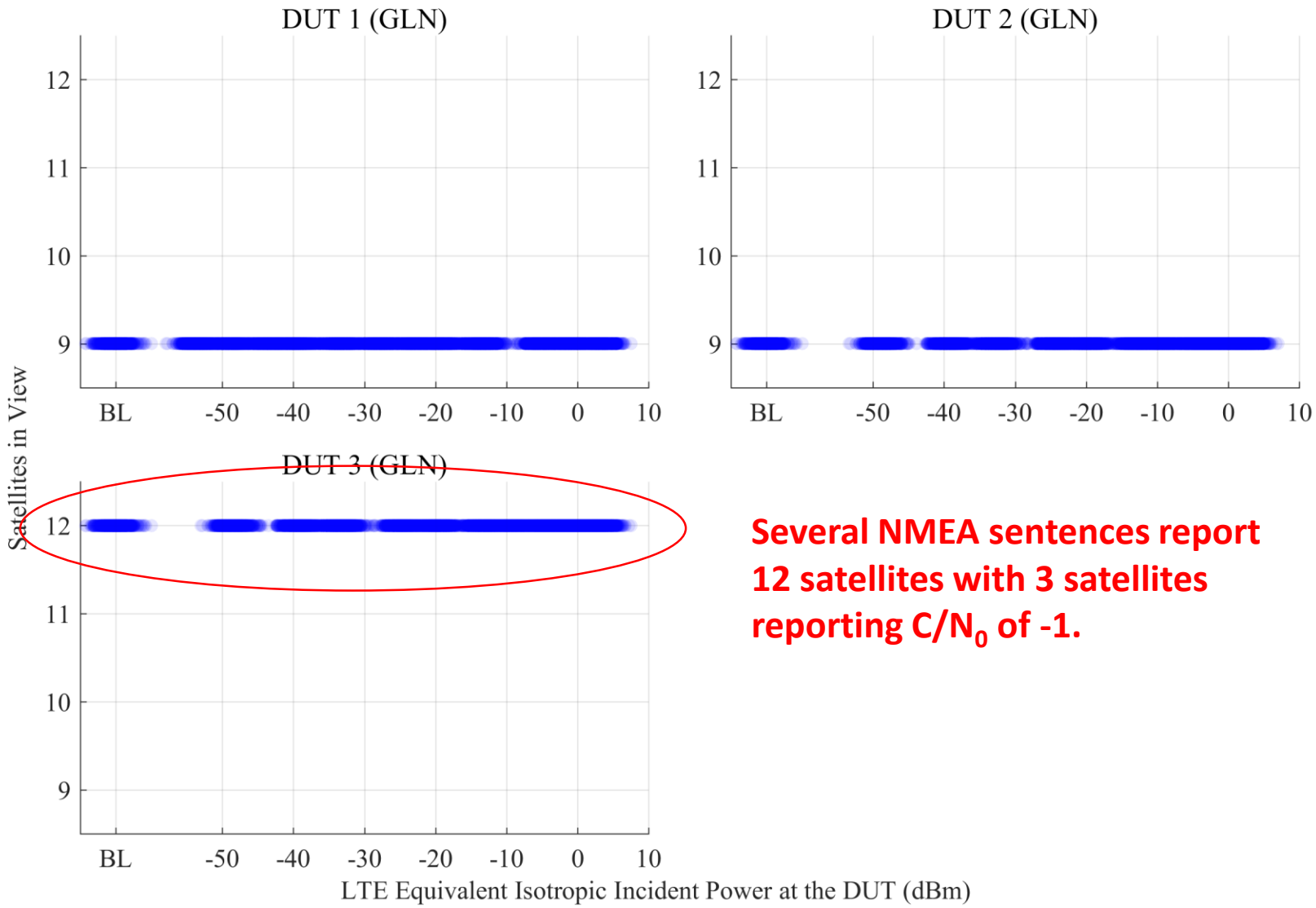


NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.112 – pg. 237

General Location

- Number of reported satellites in view scatter plot
- Downlink
- Limited satellite condition



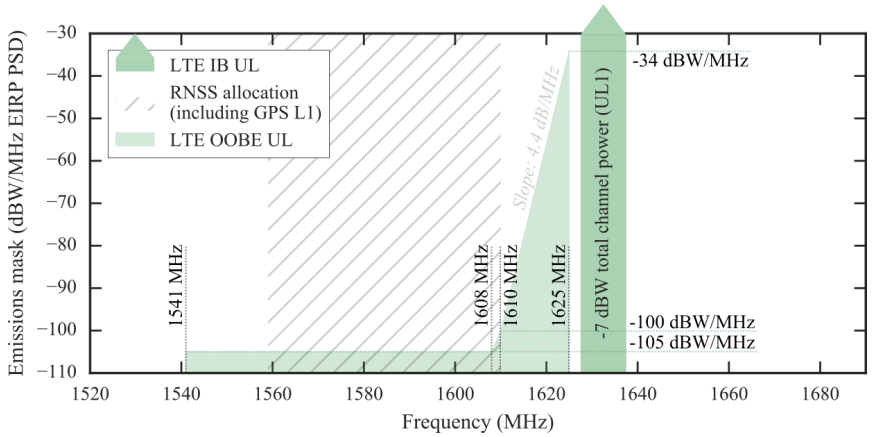
Several NMEA sentences report 12 satellites with 3 satellites reporting C/N_0 of -1.

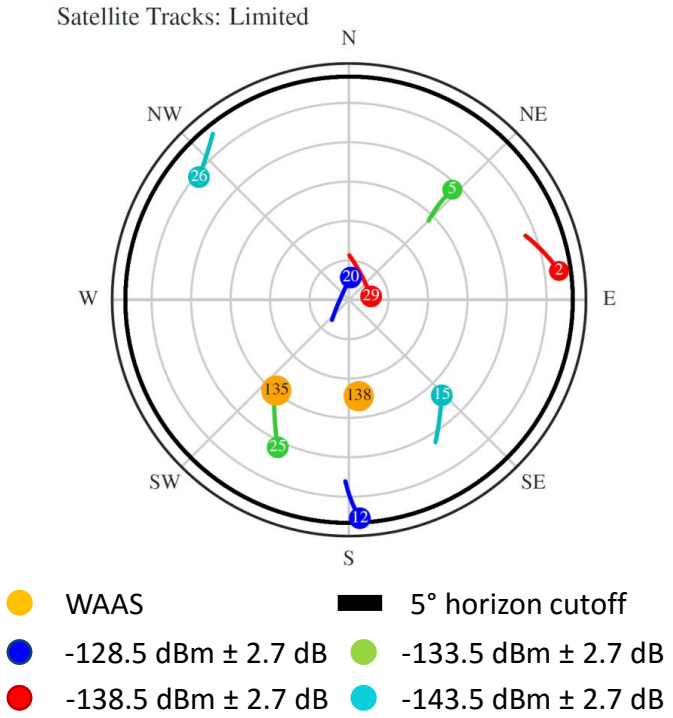
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.113 – pg. 238

General Location and Navigation

- Limited Satellite Condition
  - Downlink
  - **Uplink 1**

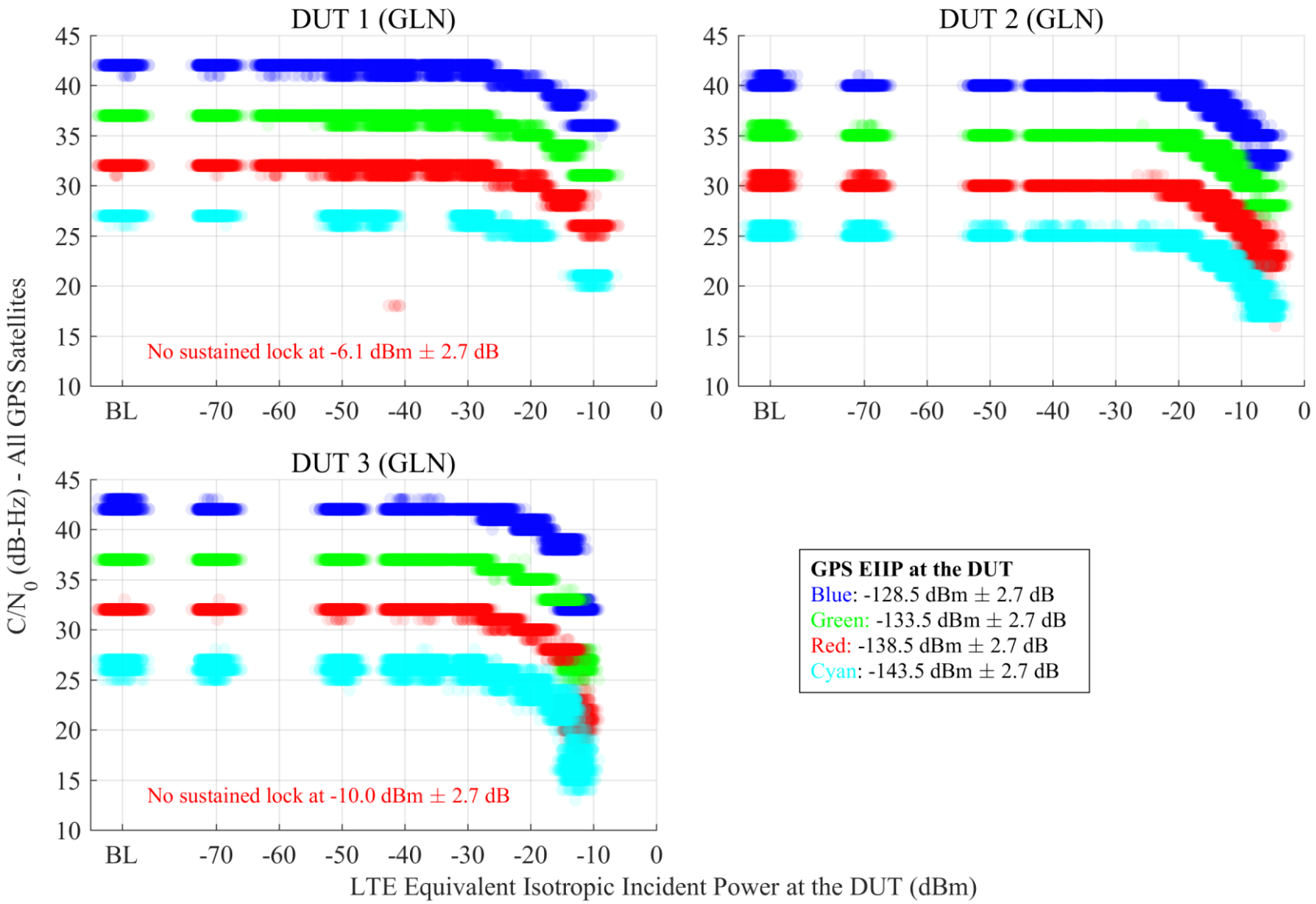




NASCTN
National Advanced Spectrum and Communications Test Network

General Location

- C/N0 scatter plots
- Uplink 1
- Limited satellite condition
- 600 points per LTE power level per satellite

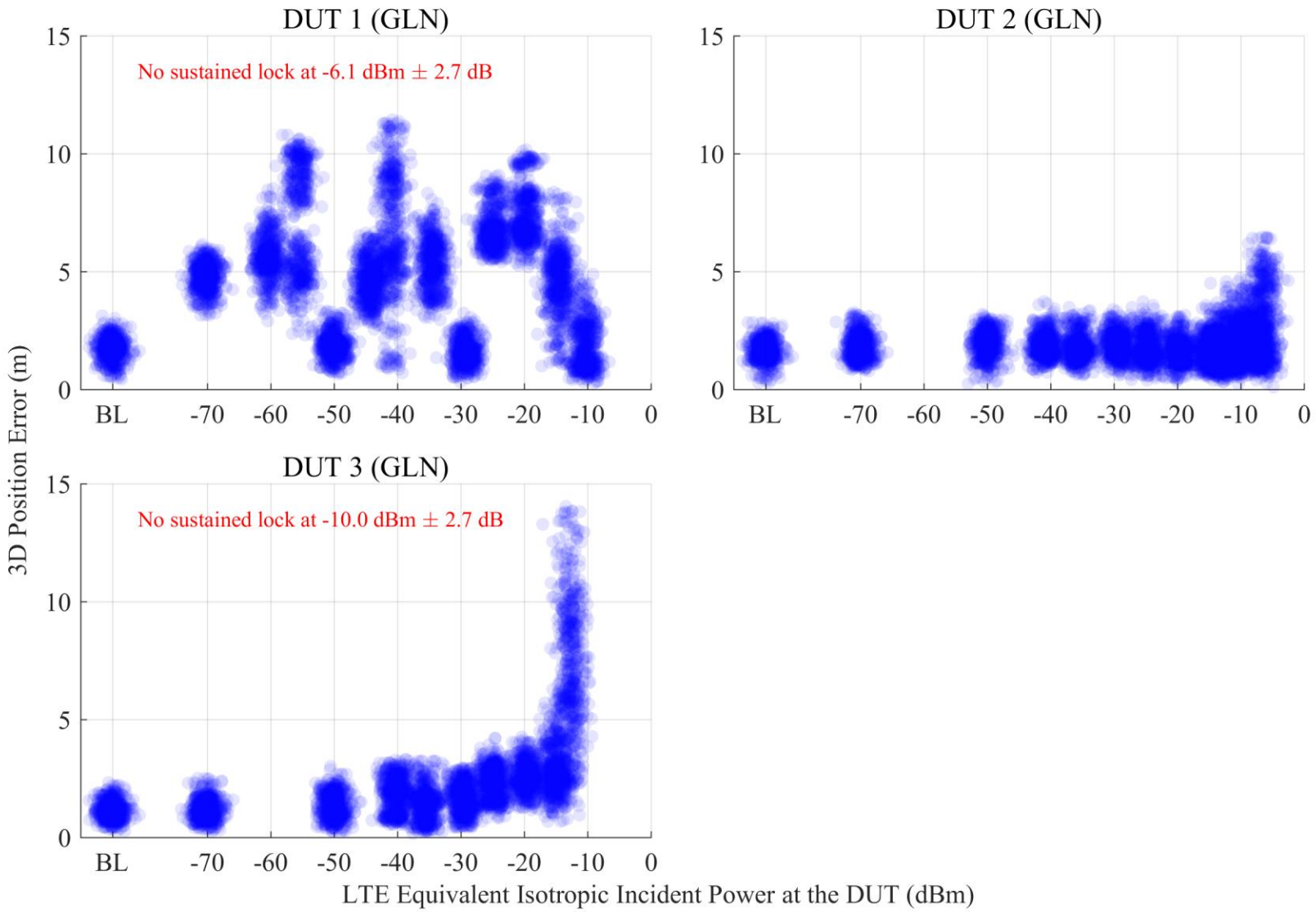


NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.114 – pg. 239

General Location

- 3D position error scatter plots
- Uplink 1
- Limited satellite condition



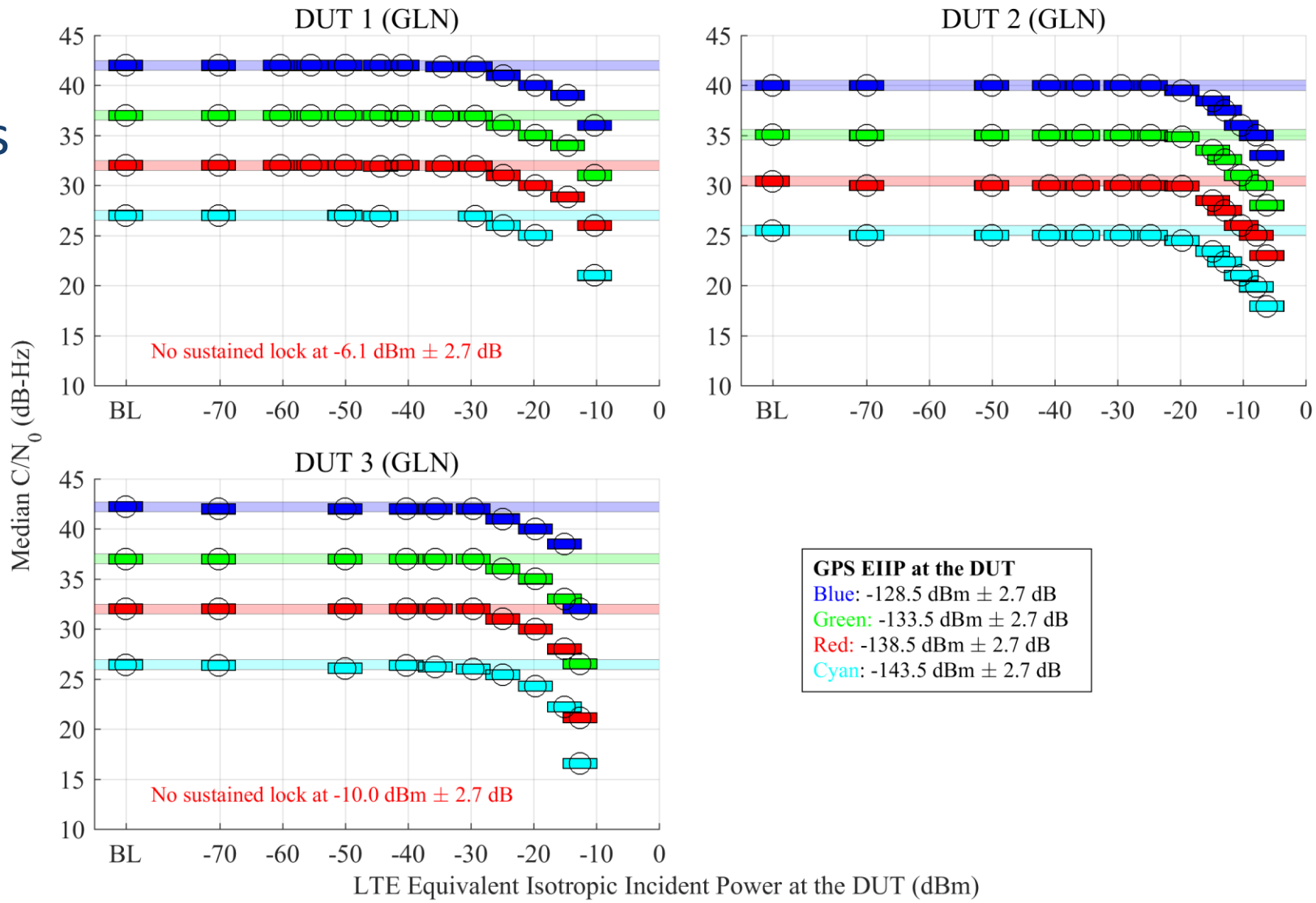
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.116 – pg. 241

General Location

- 95% confidence regions for median C/N_0
- Uplink 1
- Limited satellite condition

-128.5 dBm	Baseline (BL) – No LTE Power
-133.5 dBm	Baseline (BL) – No LTE Power
-138.5 dBm	Baseline (BL) – No LTE Power
-143.5 dBm	Baseline (BL) – No LTE Power



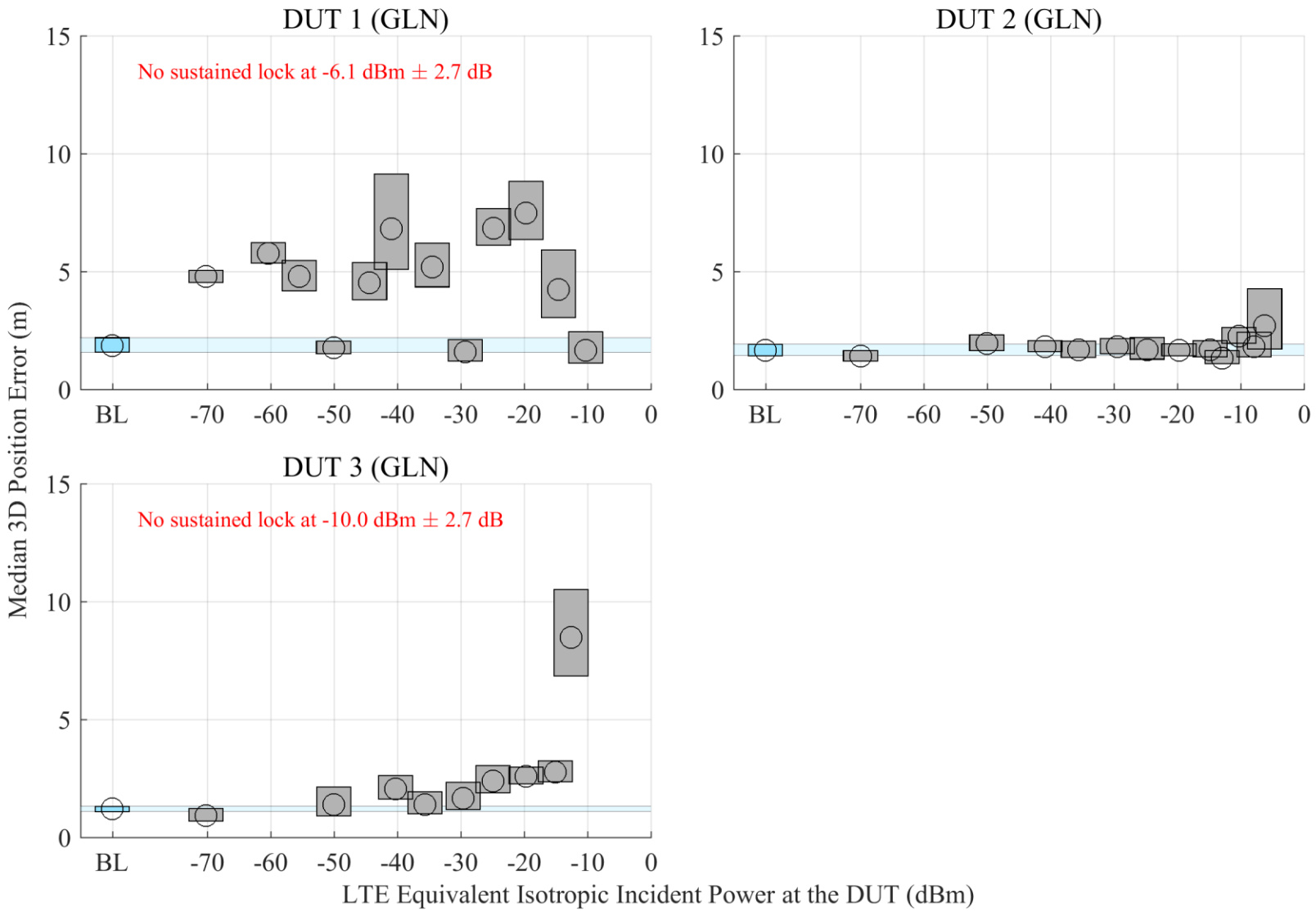
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.115 – pg. 240

General Location

- 95% confidence regions for median 3D position error
- Uplink 1
- Limited satellite condition

Baseline (BL) – No LTE Power

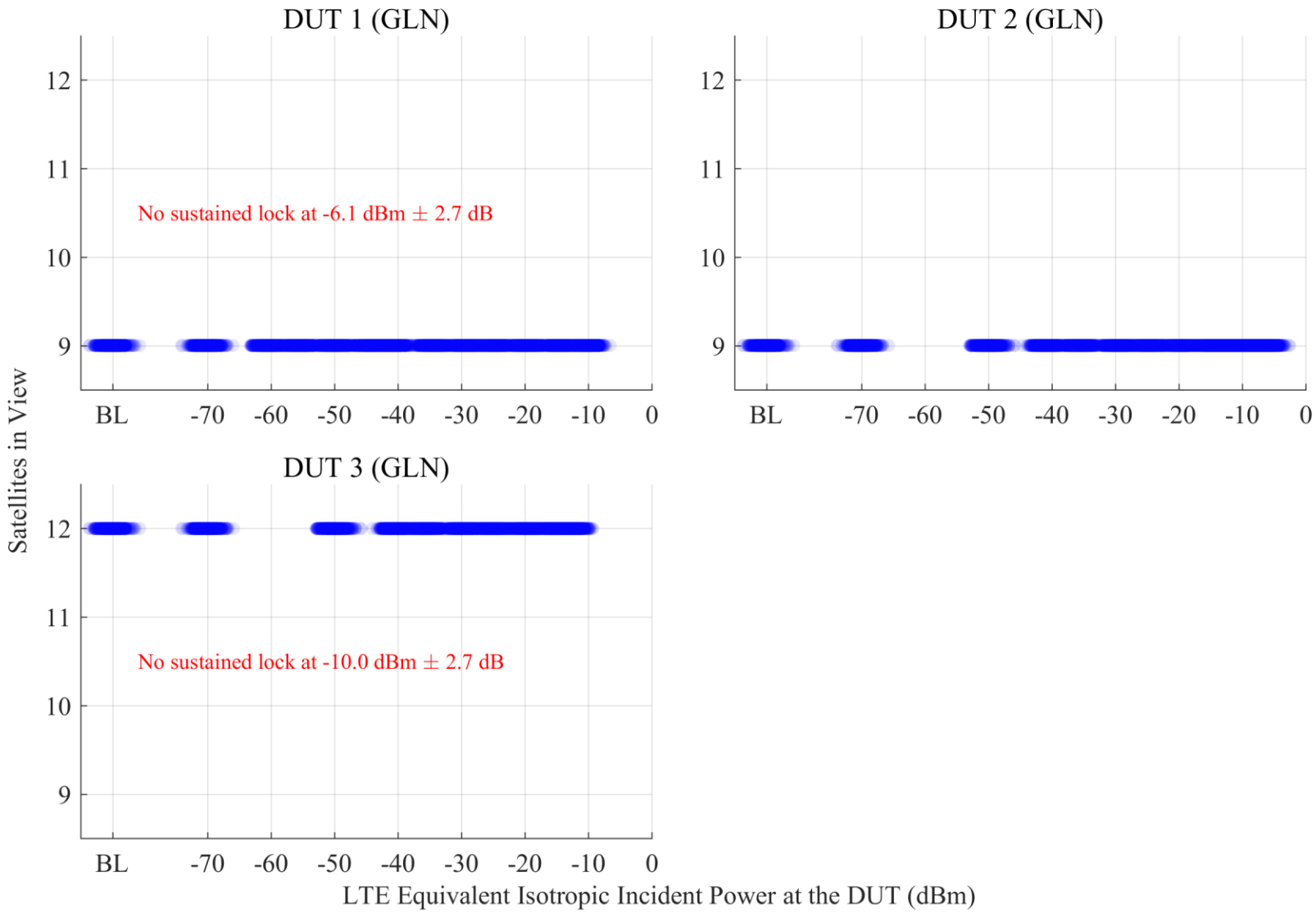


NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.117 – pg. 242

General Location

- Number of reported satellites in view scatter plot
- Uplink 1
- Limited satellite condition



NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.118 – pg. 243

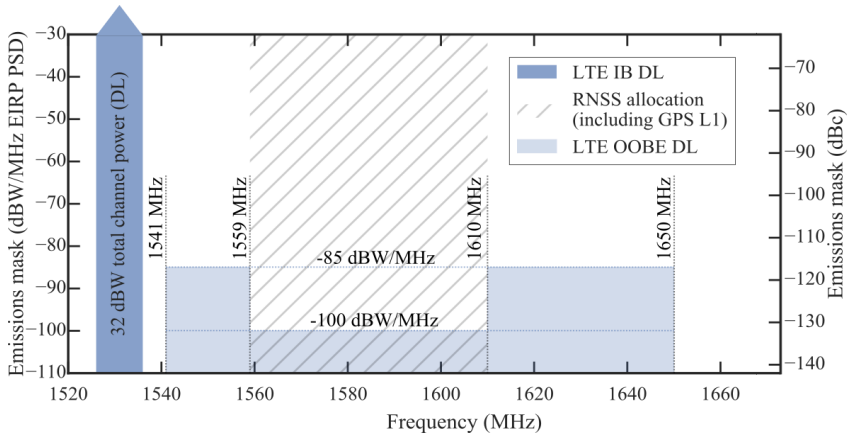
Precision Location and Real Time Kinematic

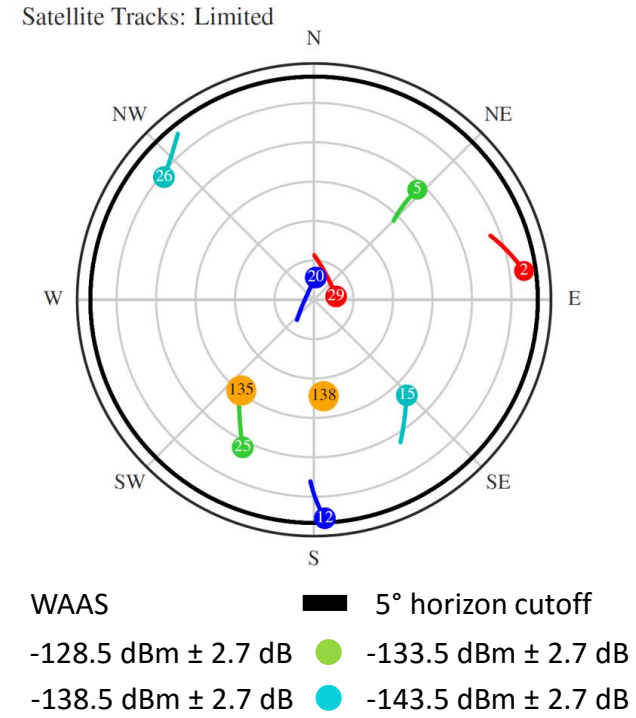
Limited Satellite Constellation

NASCTN
National Advanced Spectrum and Communications Test Network

Precision Location

- Limited Satellite Condition
  - **Downlink**
  - Uplink 1

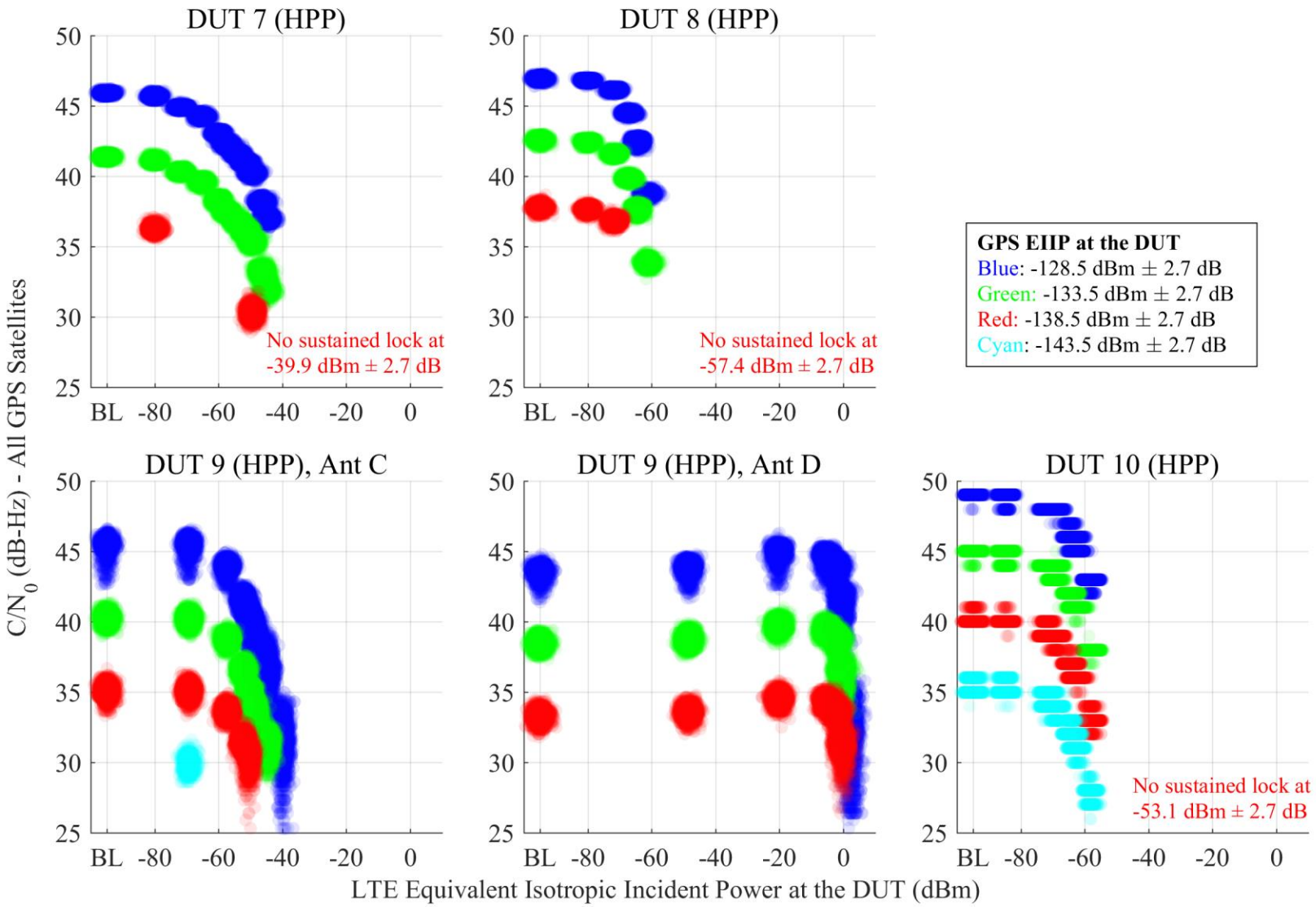




NASCTN
National Advanced Spectrum and Communications Test Network

Precision Location

- C/N0 scatter plots
- Downlink
- Limited satellite condition
- 1200 points per LTE power level per satellite

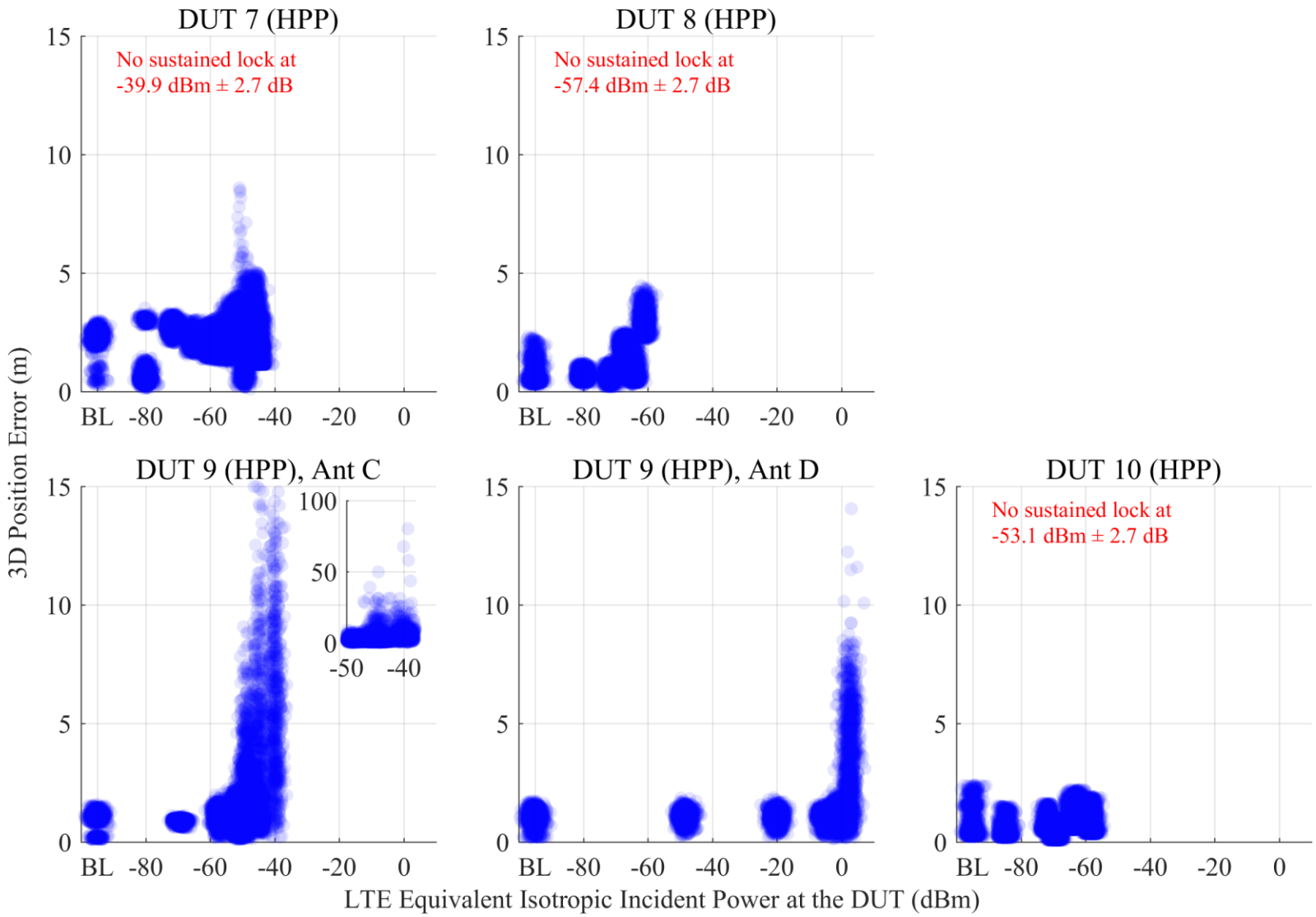


NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.119 – pg. 244

Precision Location

- 3D position error scatter plots
- Downlink
- Limited satellite condition



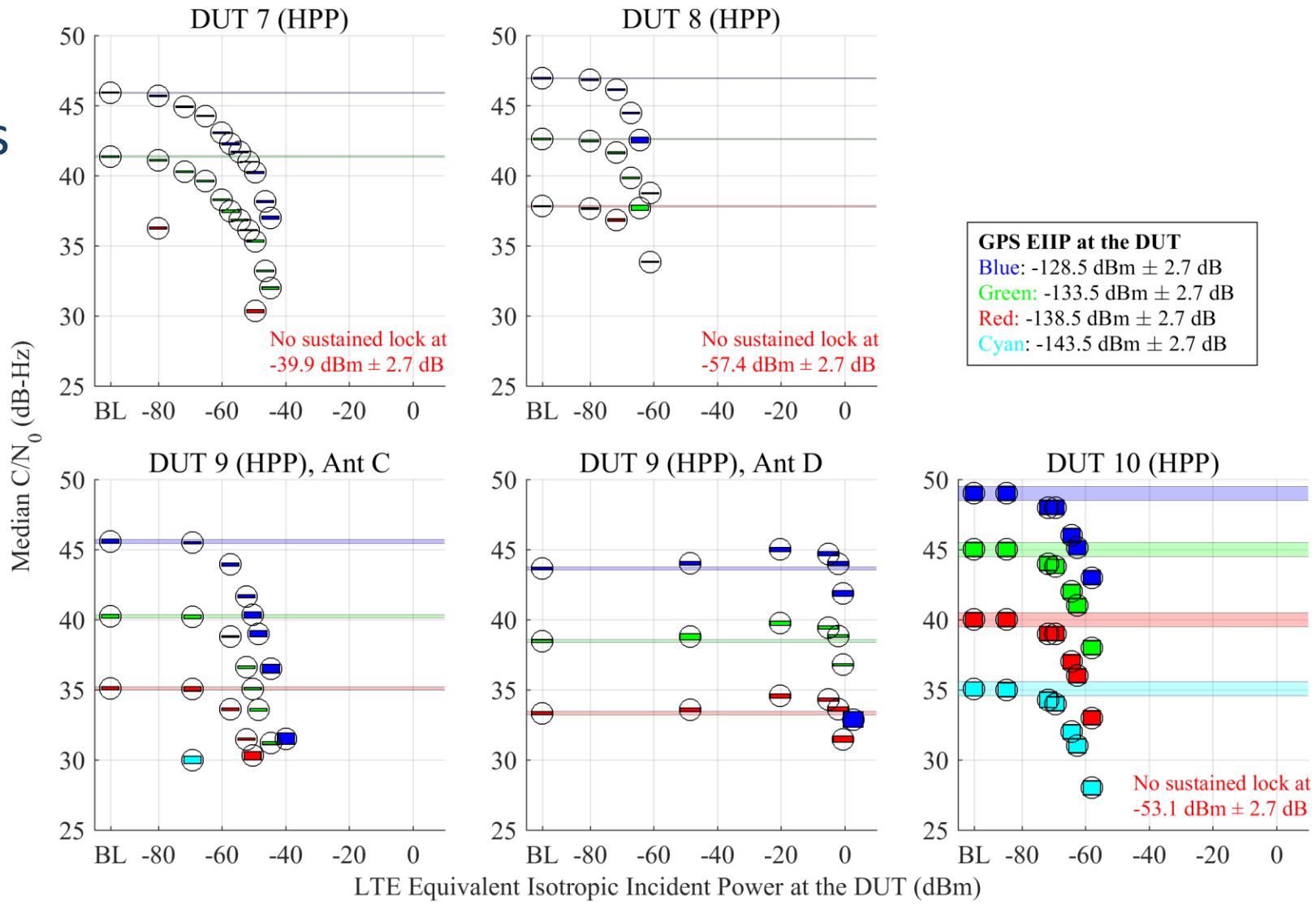
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.121 – pg. 246

Precision Location

- 95% confidence regions for median C/N_0
- Downlink
- Limited satellite condition

-128.5 dBm	Baseline (BL) – No LTE Power
-133.5 dBm	Baseline (BL) – No LTE Power
-138.5 dBm	Baseline (BL) – No LTE Power
-143.5 dBm	Baseline (BL) – No LTE Power



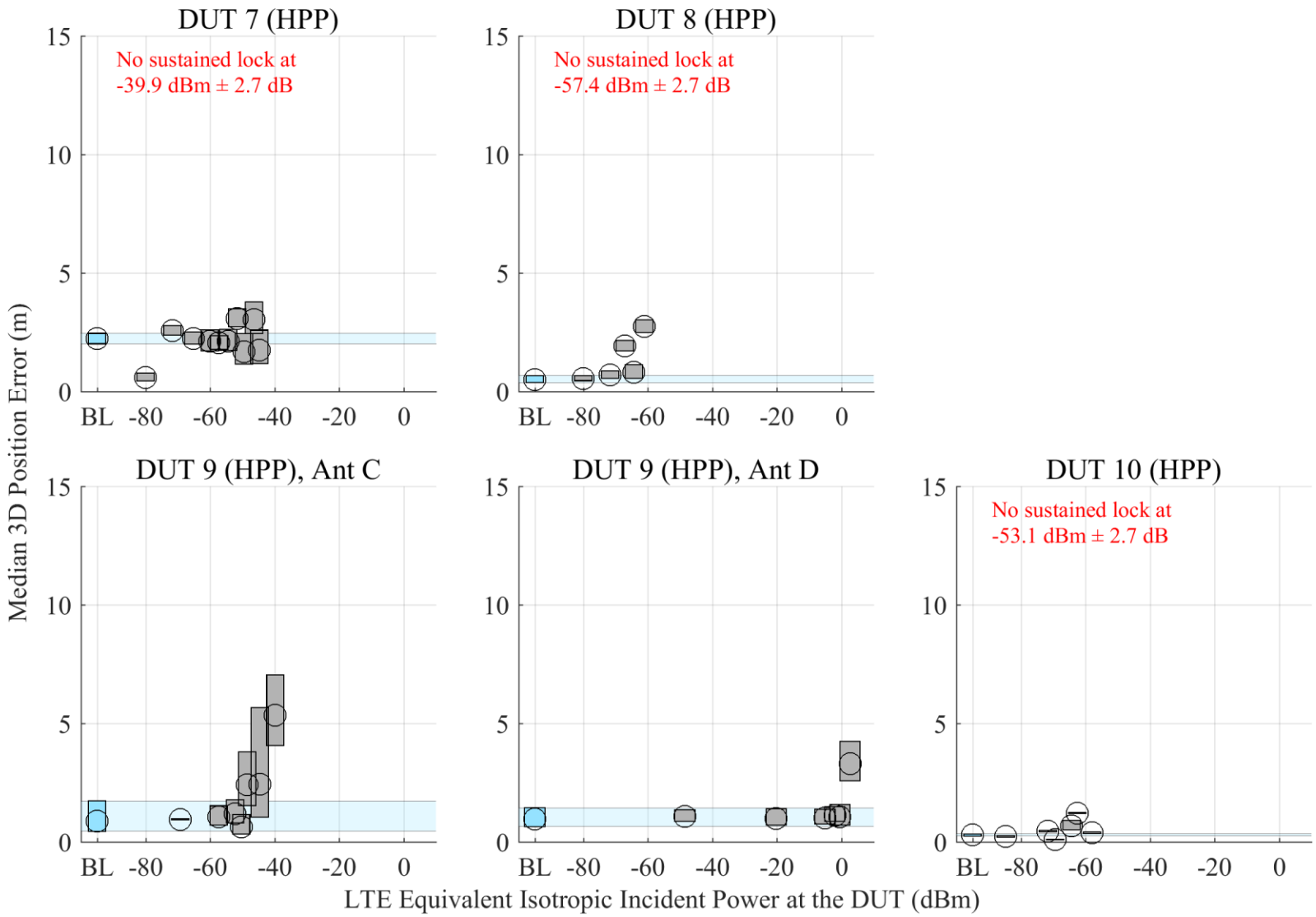
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.120 – pg. 245

Precision Location

- 95% confidence regions for median 3D position error
- Downlink
- Limited satellite condition

Baseline (BL) – No LTE Power

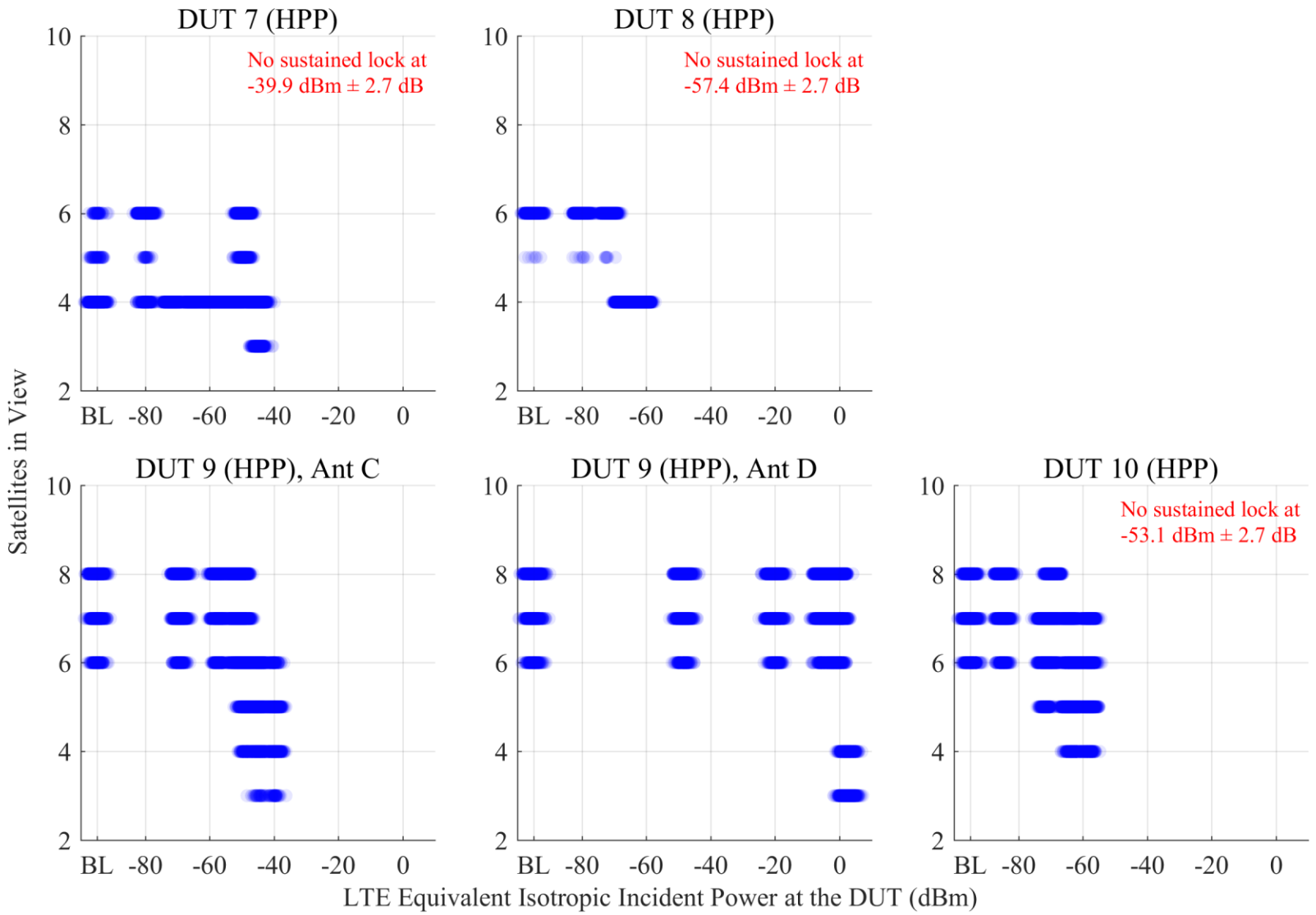


NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.122 – pg. 247

Precision Location

- Number of reported satellites in view scatter plot
- Downlink
- Limited satellite condition



NASCTN
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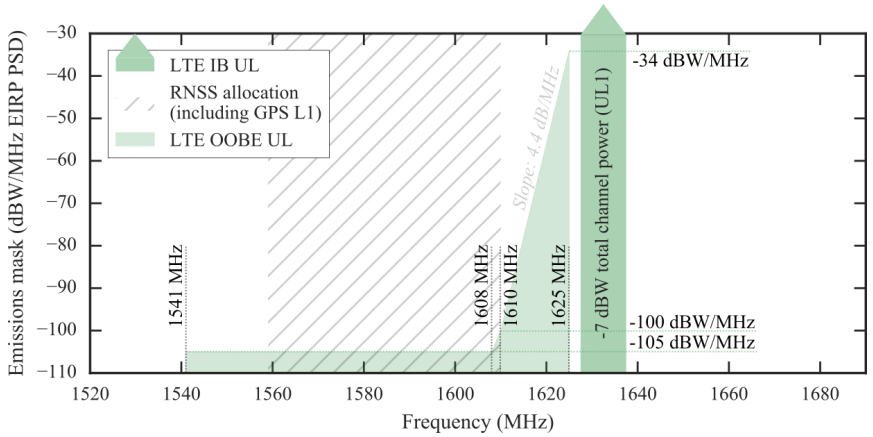
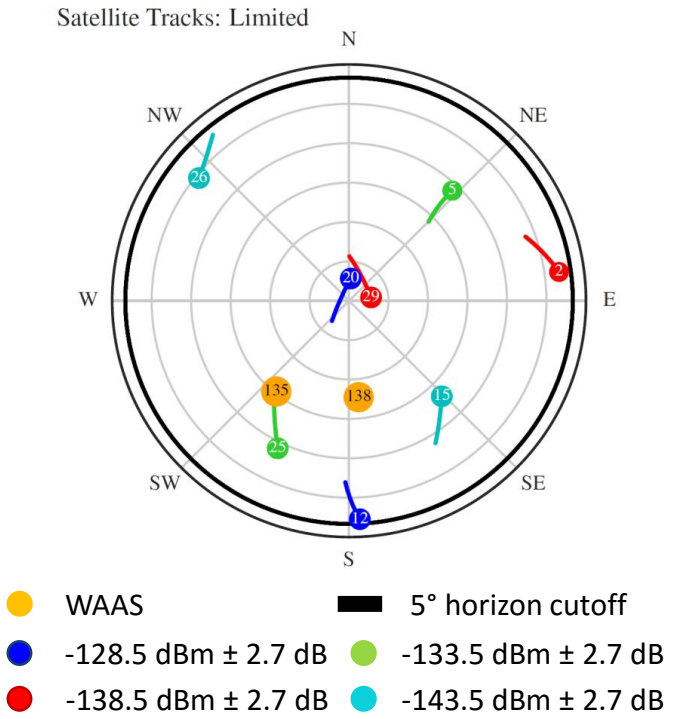
Fig. 6.123 – pg. 248

Precision Location

- Limited Satellite Condition
  - Downlink
  - **Uplink 1**





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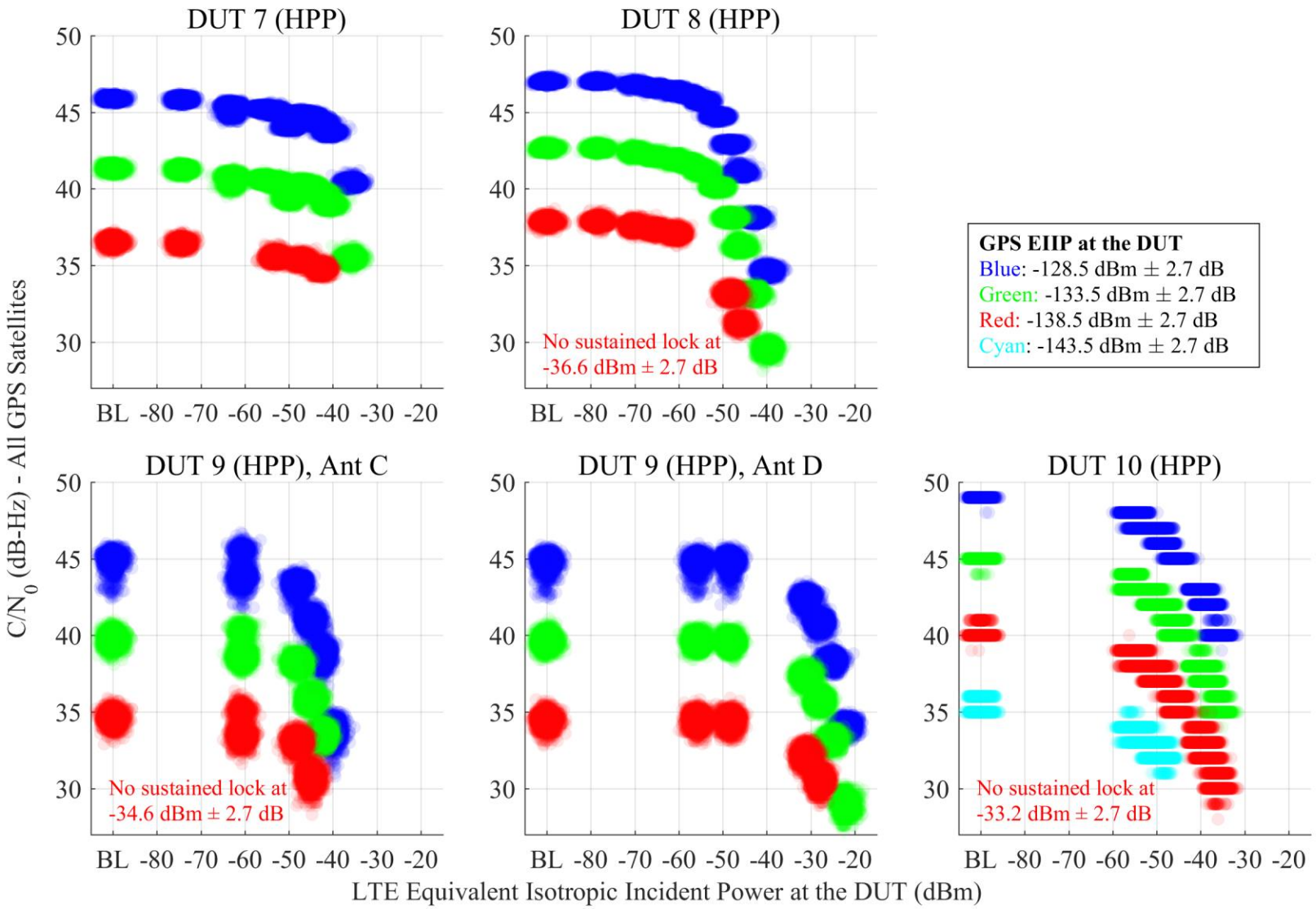
Precision Location

- C/N0 scatter plots
- Uplink 1
- Limited satellite condition
- 1200 points per LTE power level per satellite



NASCTN
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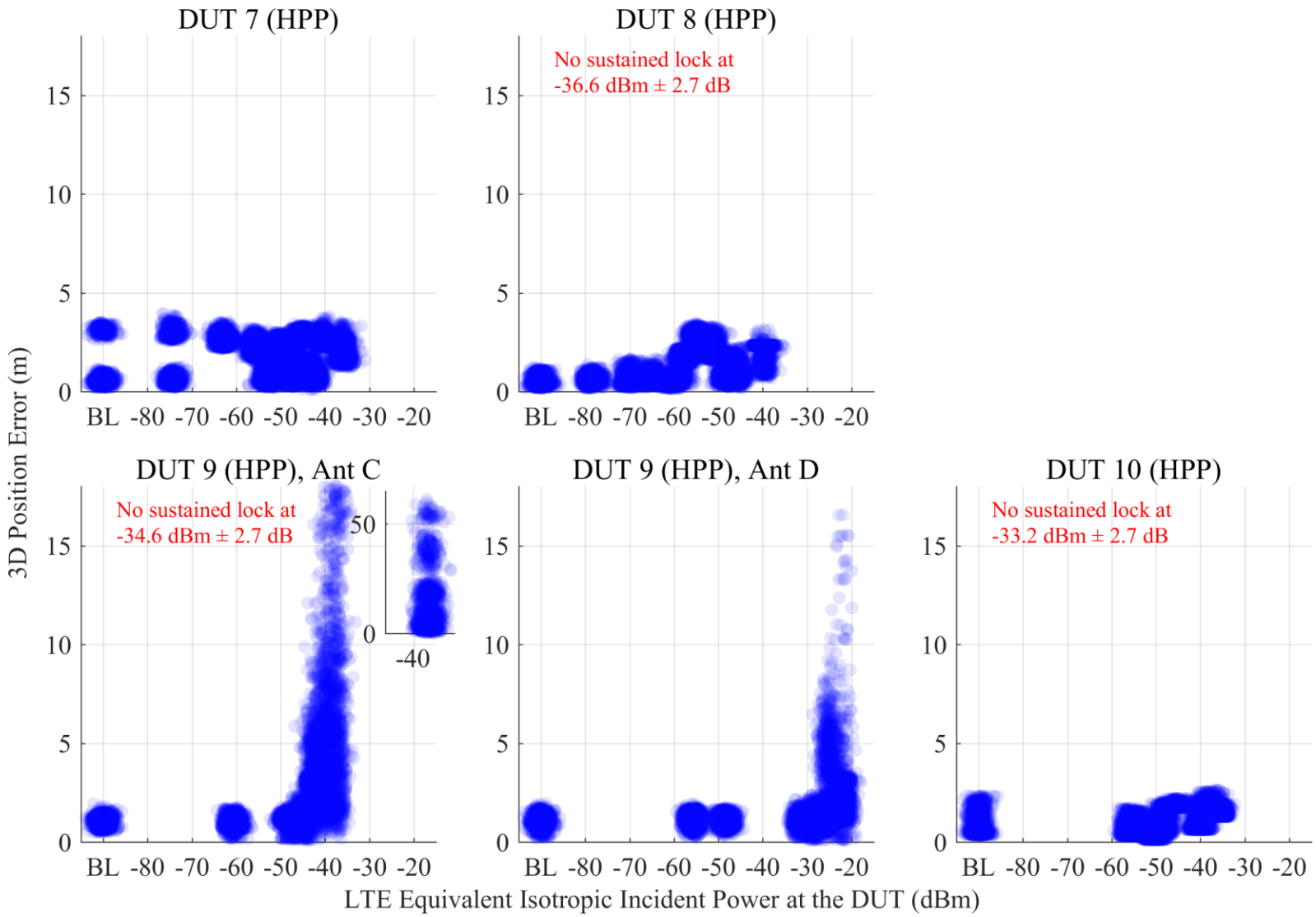
Fig. 6.124 – pg. 249

Precision Location

- 3D position error scatter plots
- Uplink 1
- Limited satellite condition



NASCTN
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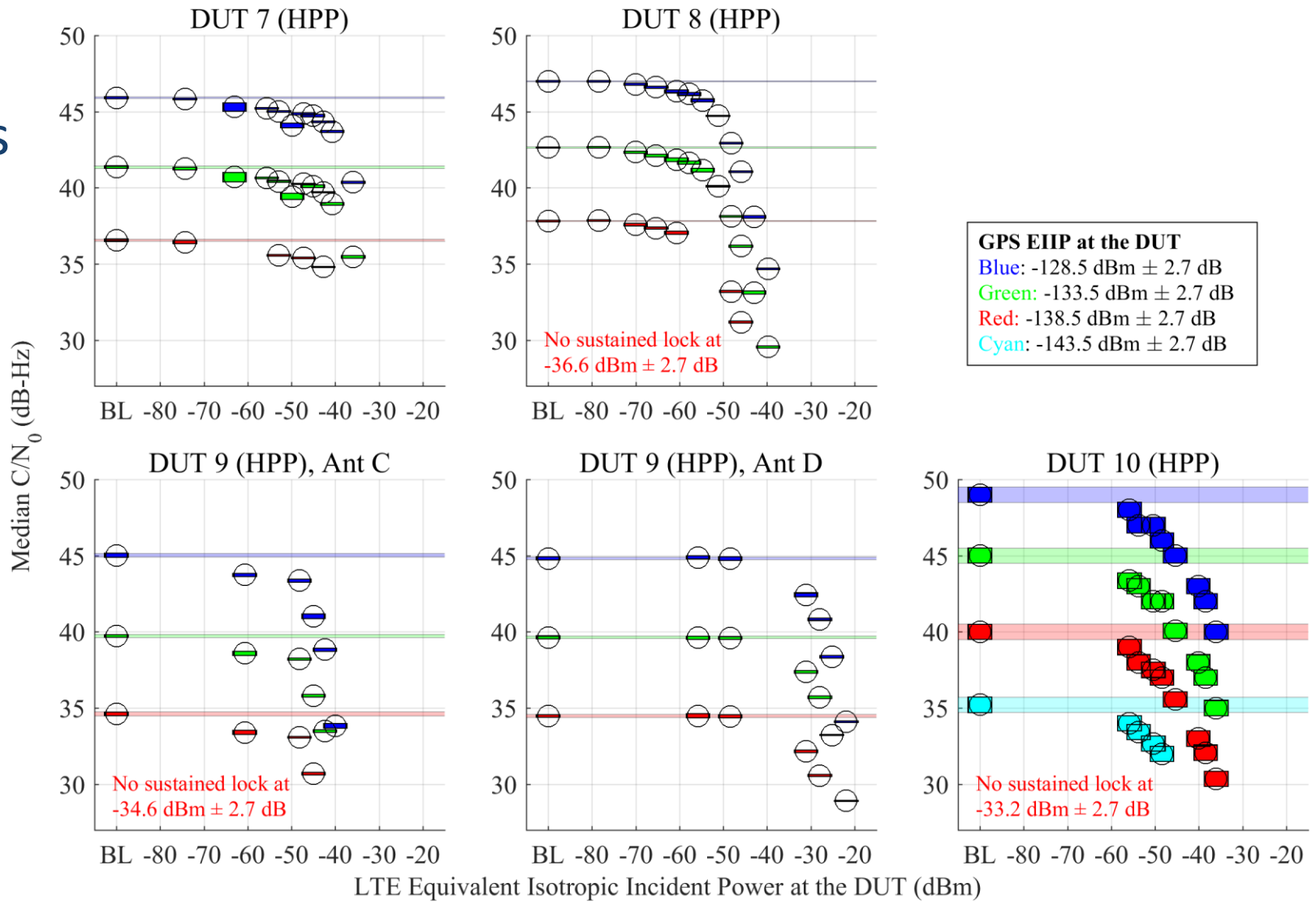
Fig. 6.126 – pg. 251

Precision Location

- 95% confidence regions for median C/N_0
- Uplink 1
- Limited satellite condition

-128.5 dBm	Baseline (BL) – No LTE Power
-133.5 dBm	Baseline (BL) – No LTE Power
-138.5 dBm	Baseline (BL) – No LTE Power
-143.5 dBm	Baseline (BL) – No LTE Power



NASCTN
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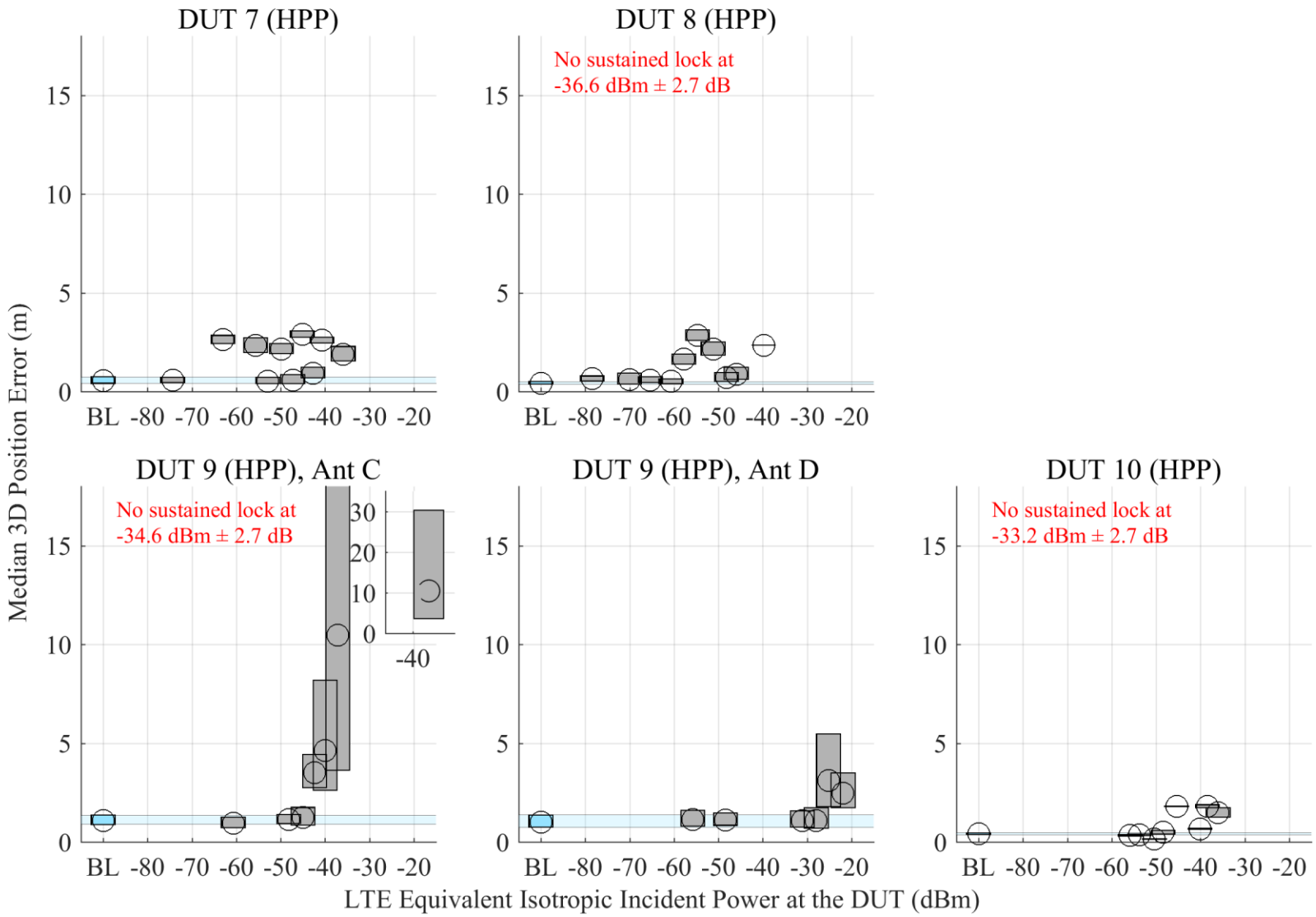
Fig. 6.125 – pg. 250

Precision Location

- 95% confidence regions for median 3D position error
- Uplink 1
- Limited satellite condition

Baseline (BL) – No LTE Power

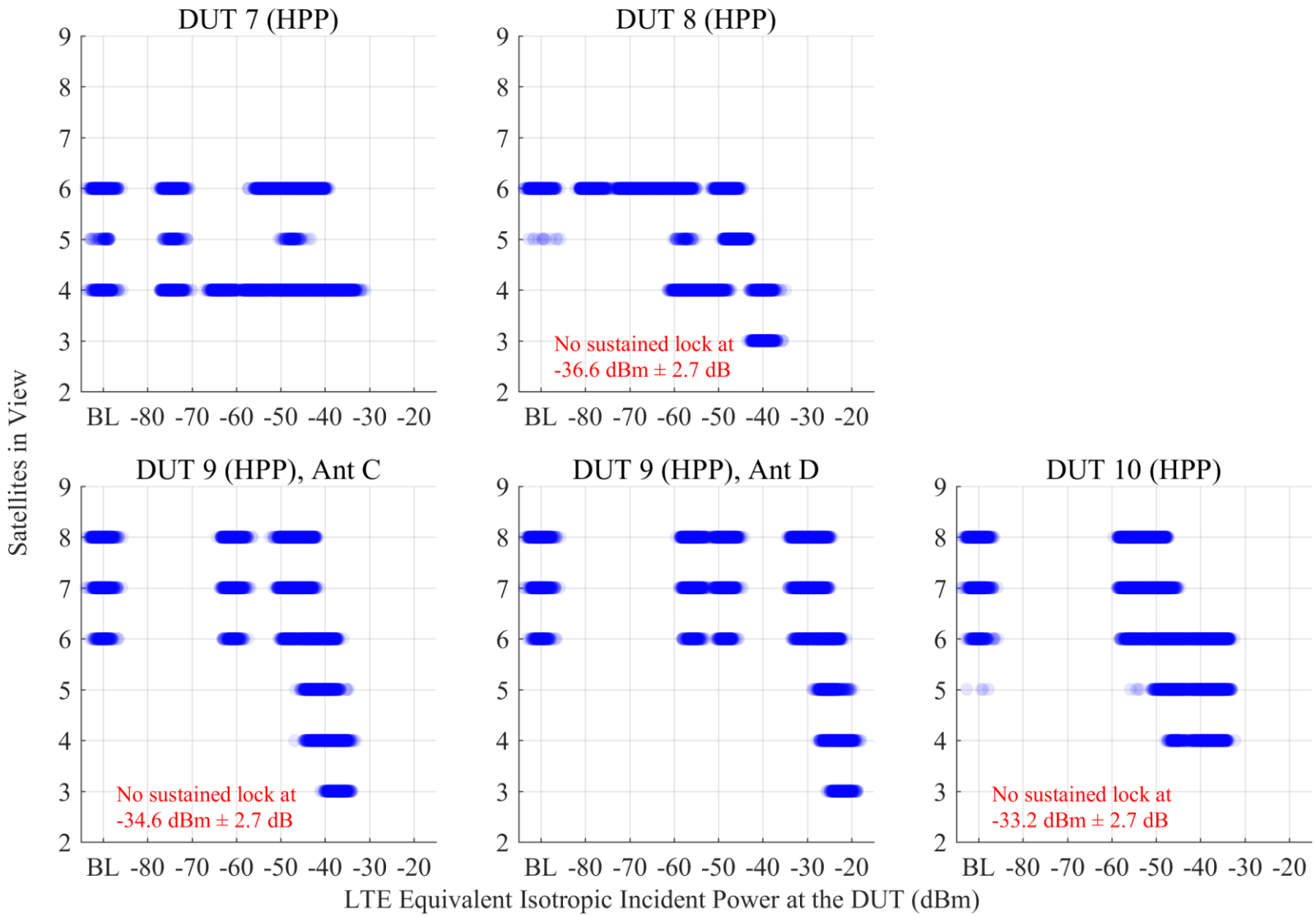


NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.127 – pg. 252

Precision Location

- Number of reported satellites in view scatter plot
- Uplink 1
- Limited satellite condition

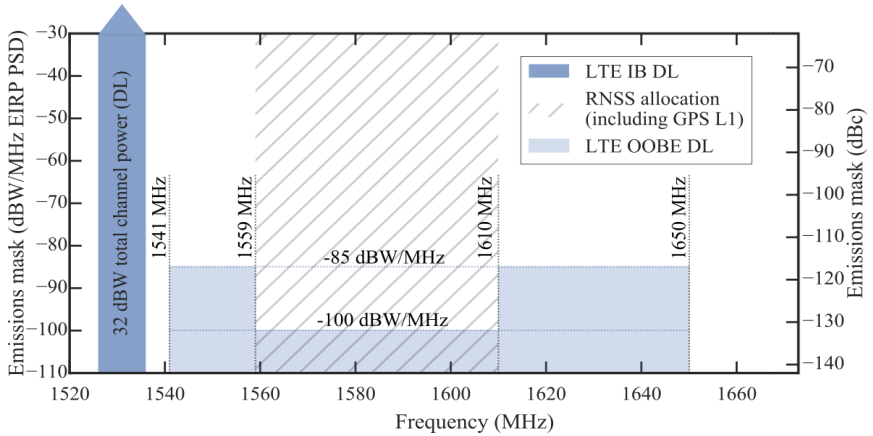


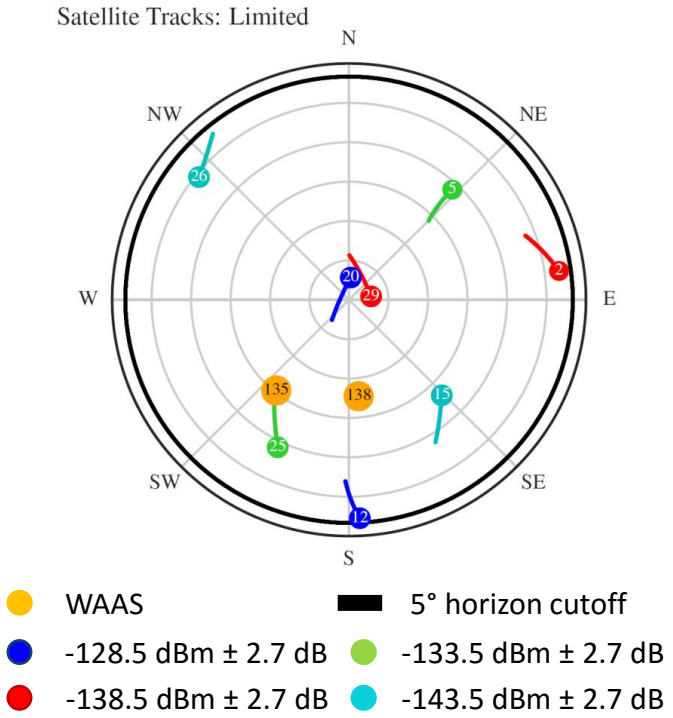
NASCTN
National Advanced Spectrum and Communications Test Network

Fig. 6.128 – pg. 253

Real Time Kinematic

- Limited Satellite Condition
  - **Downlink**
  - Uplink 1





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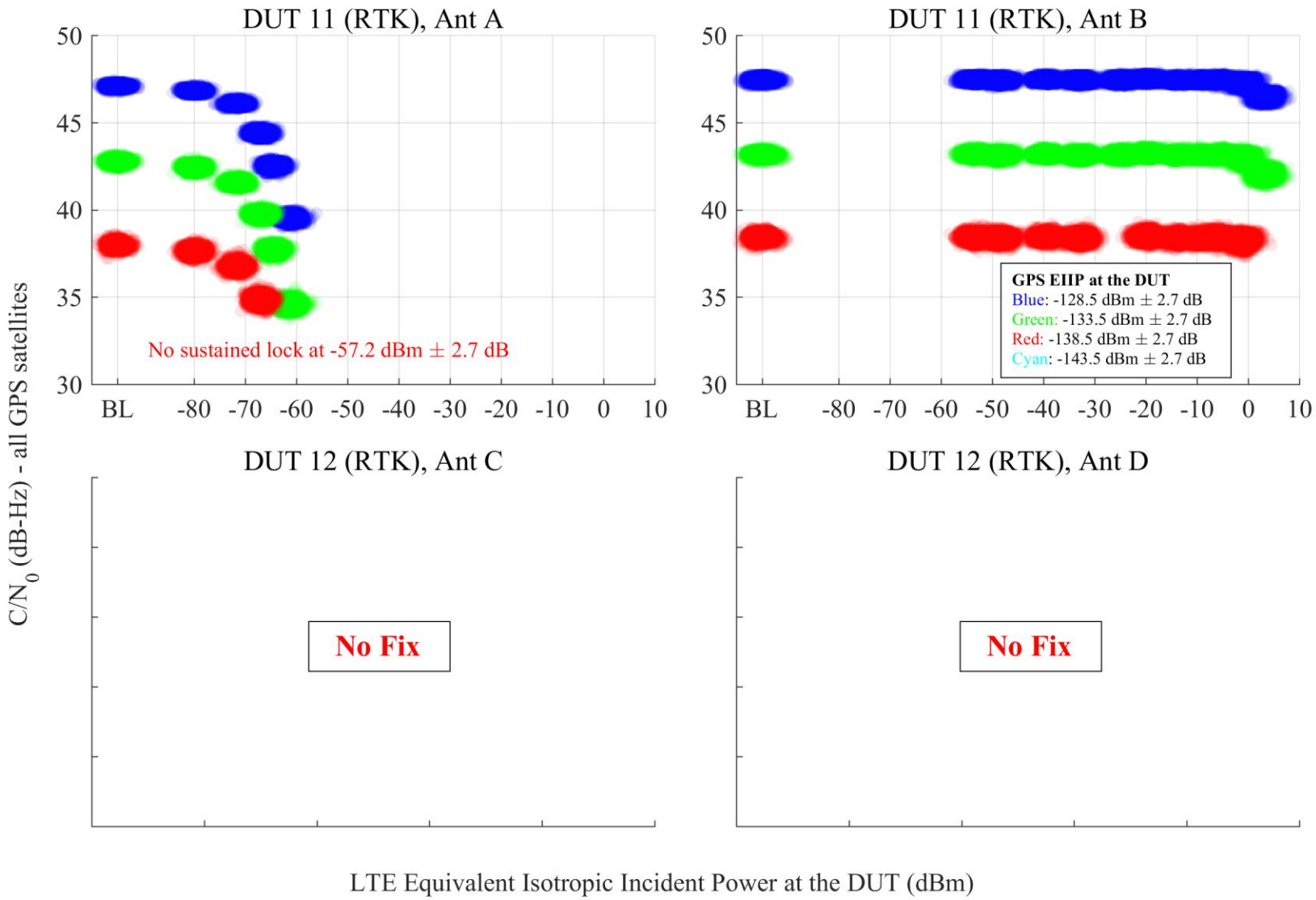
Real Time Kinematic

- C/N0 scatter plots
- Downlink
- Limited satellite condition
- 1200 points per LTE power level per satellite



NASCTN
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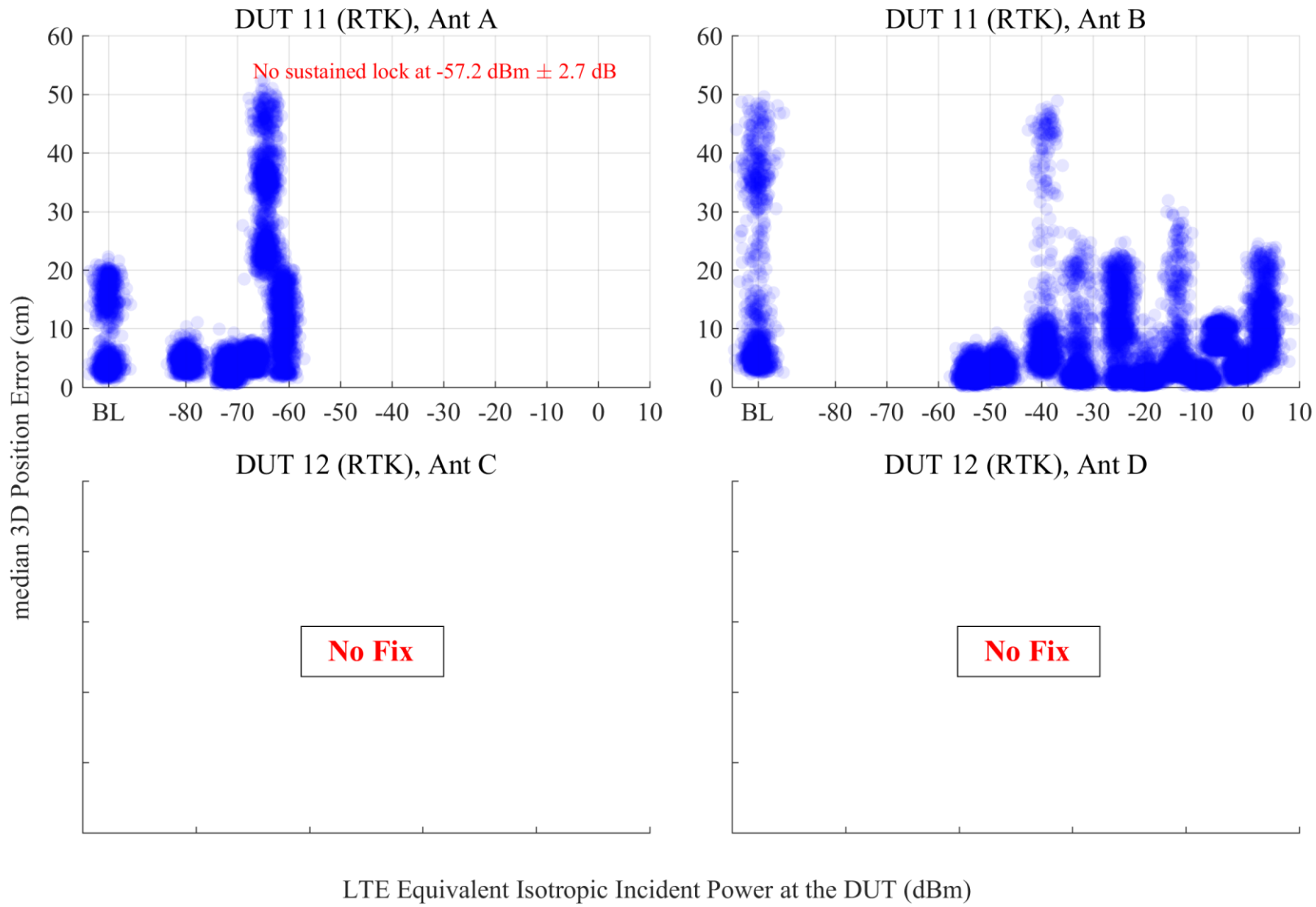
Fig. 6.129 – pg. 254

Real Time Kinematic

- 3D position error scatter plots
- Downlink
- Limited satellite condition



NASCTN
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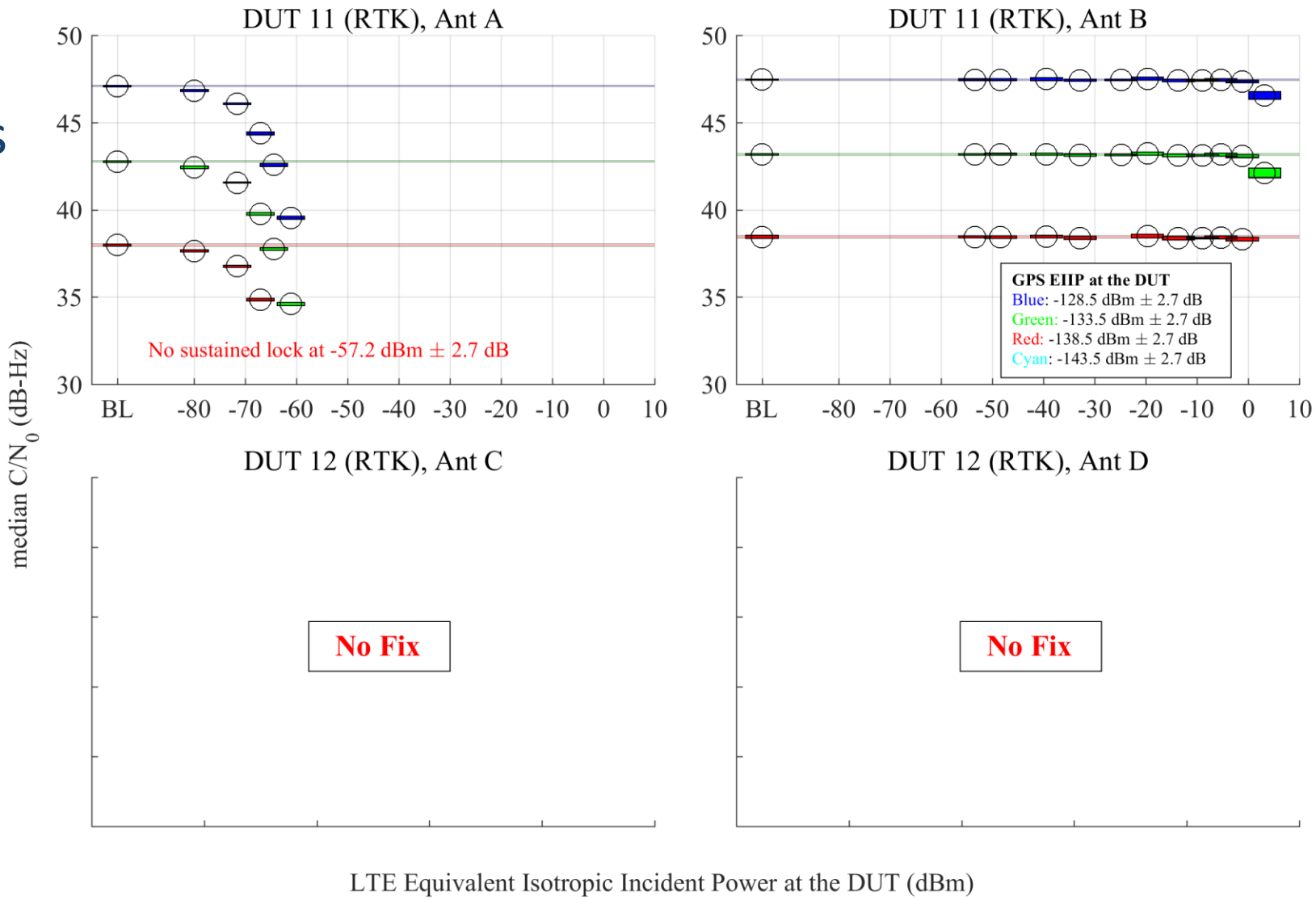
Fig. 6.131 – pg. 256

Real Time Kinematic

- 95% confidence regions for median C/N_0
- Downlink
- Limited satellite condition

-128.5 dBm	Baseline (BL) – No LTE Power
-133.5 dBm	Baseline (BL) – No LTE Power
-138.5 dBm	Baseline (BL) – No LTE Power
-143.5 dBm	Baseline (BL) – No LTE Power



NASCTN
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Fig. 6.130 – pg. 255

Real Time Kinematic

- 95% confidence regions for median 3D position error
- Downlink
- Limited satellite condition

Baseline (BL) – No LTE Power

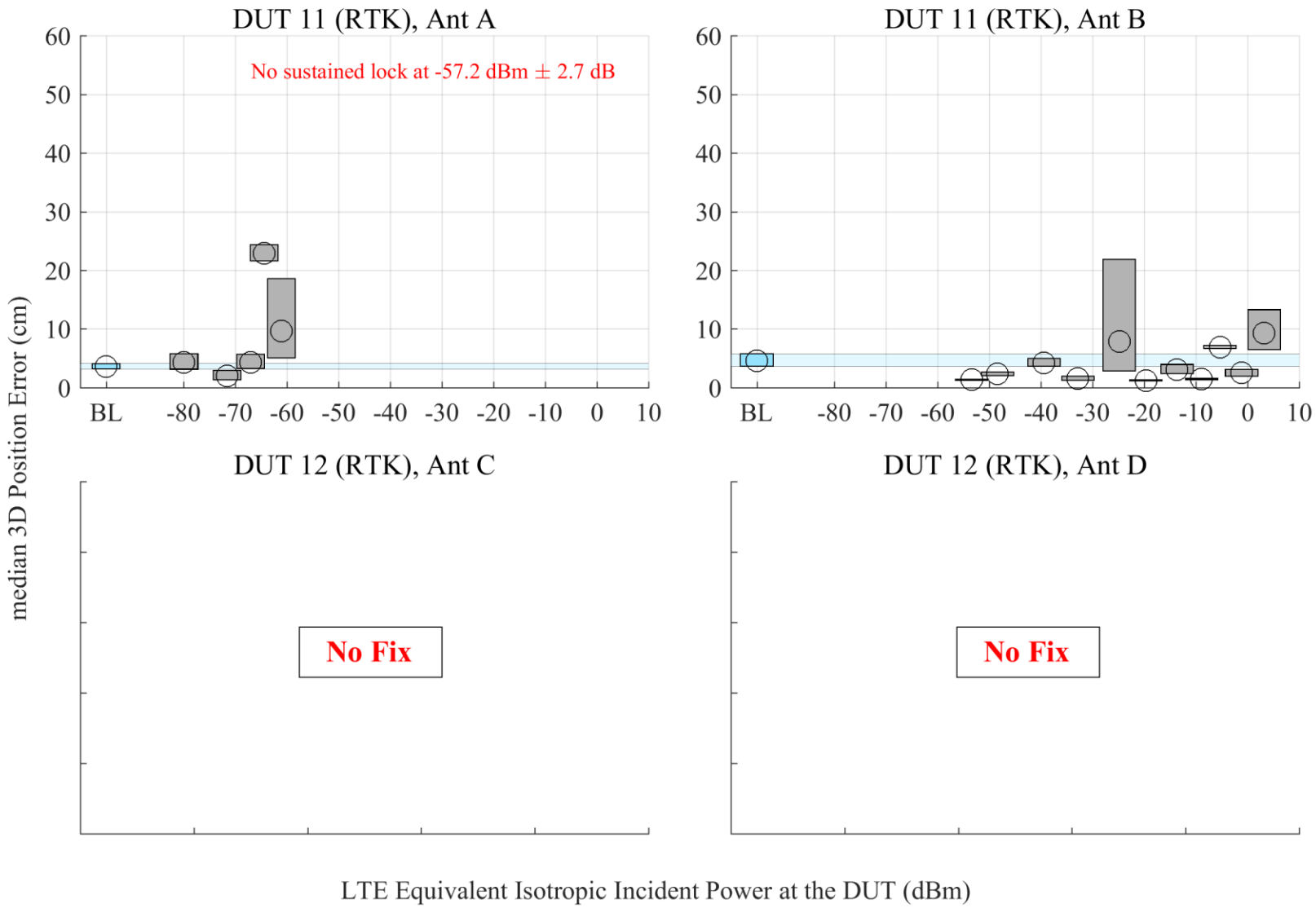

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Fig. 6.132 – pg. 257

Real Time Kinematic

- Number of reported satellites in view scatter plot
- Downlink
- Limited satellite condition

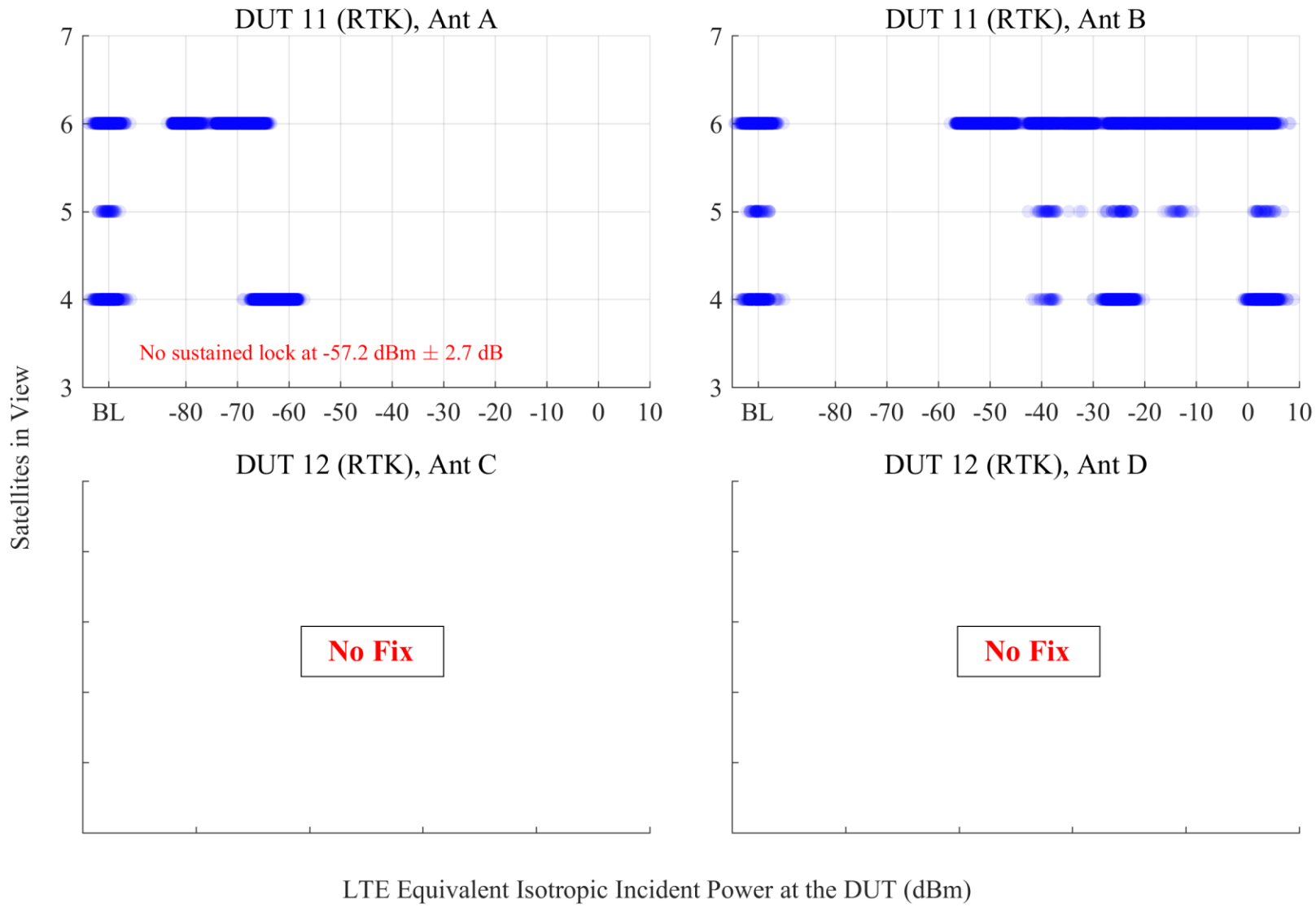

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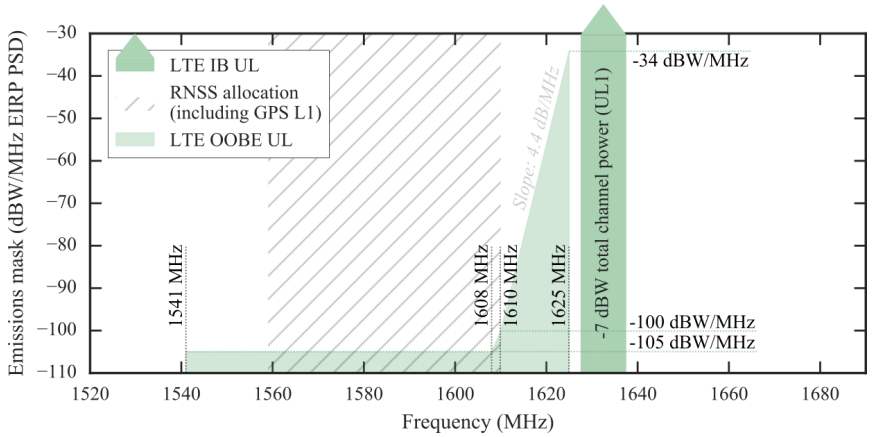
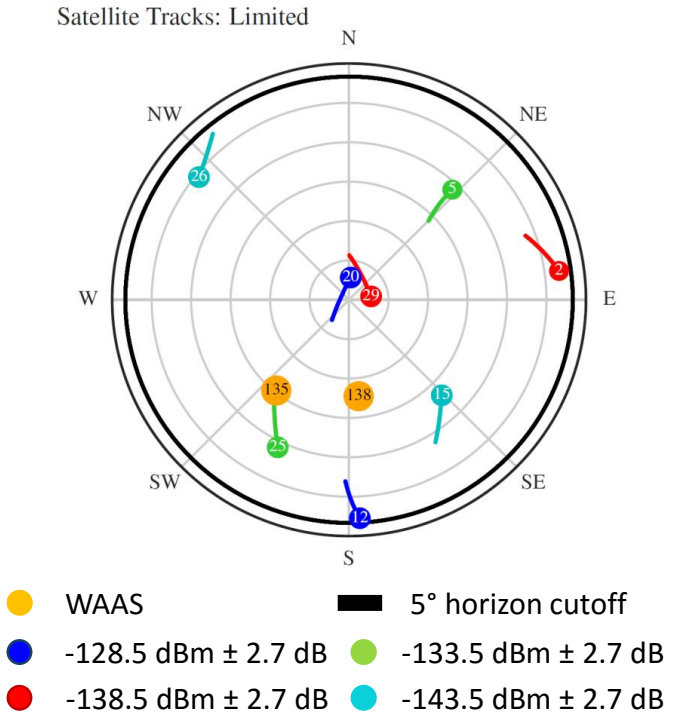
Fig. 6.133 – pg. 258

Real Time Kinematic

- Limited Satellite Condition
  - Downlink
  - **Uplink 1**





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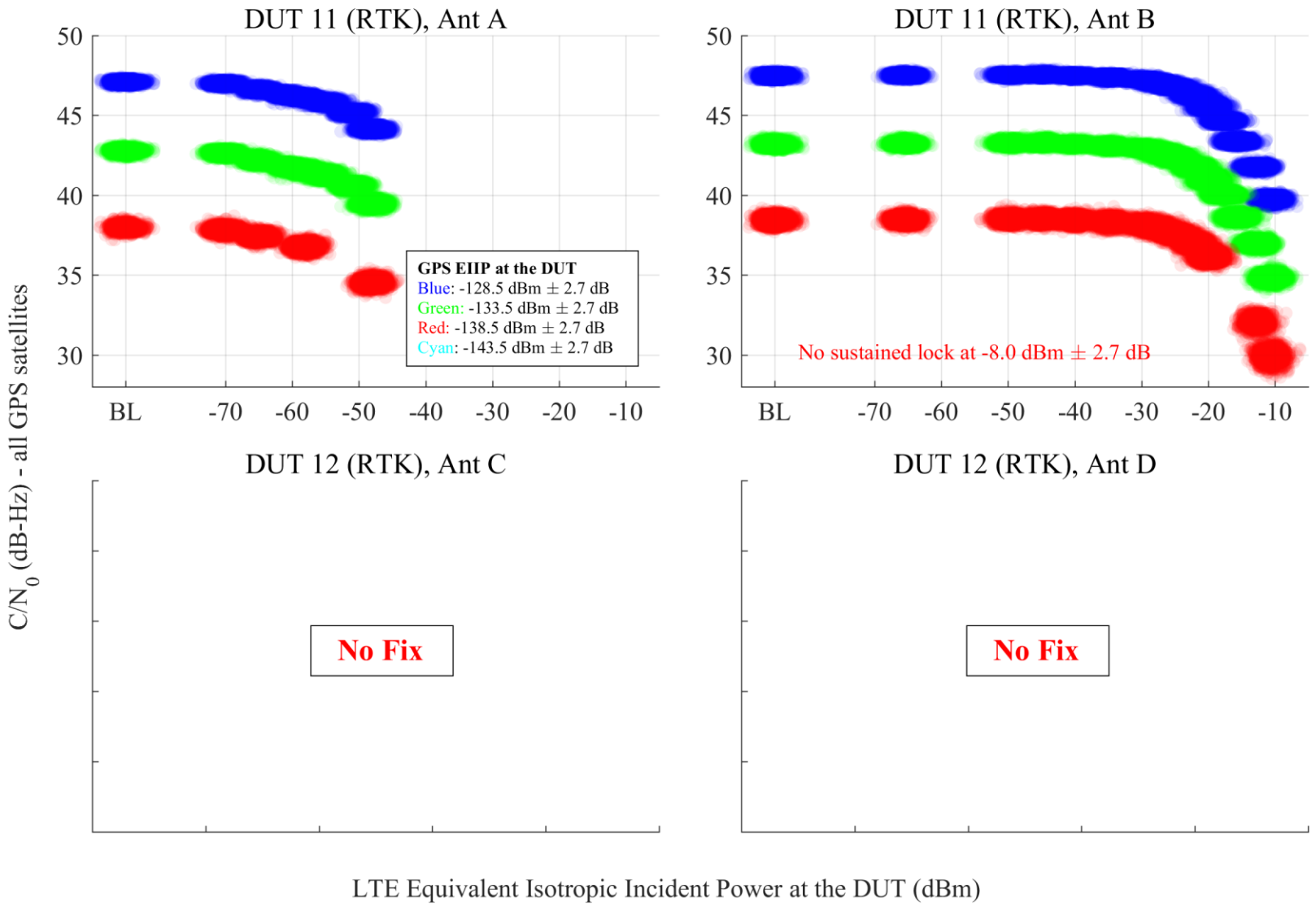
Real Time Kinematic

- C/N0 scatter plots
- Uplink 1
- Limited satellite condition
- 1200 points per LTE power level per satellite



NASCTN
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Fig. 6.134 – pg. 259

Real Time Kinematic

- 3D position error scatter plots
- Uplink 1
- Limited satellite condition

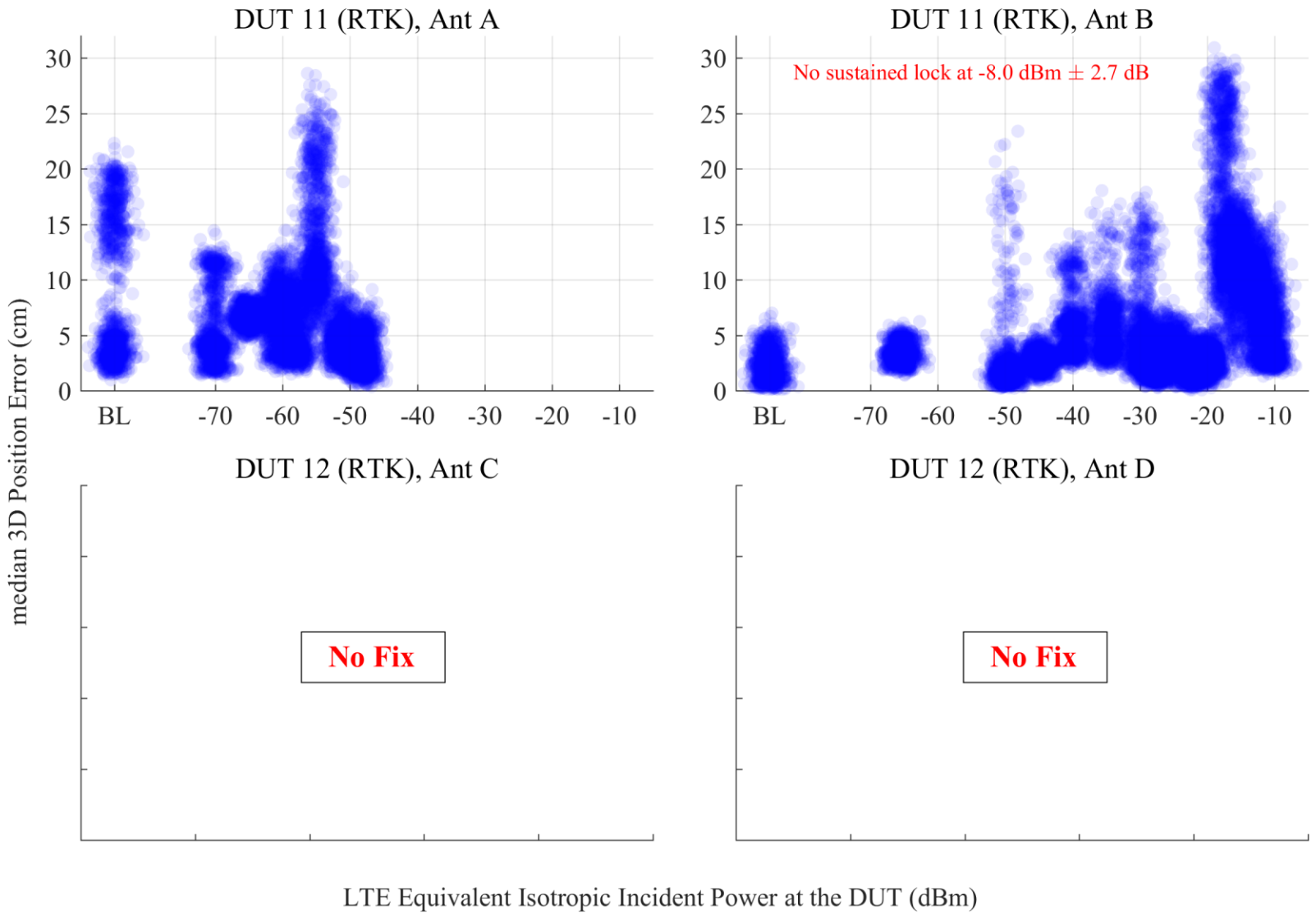

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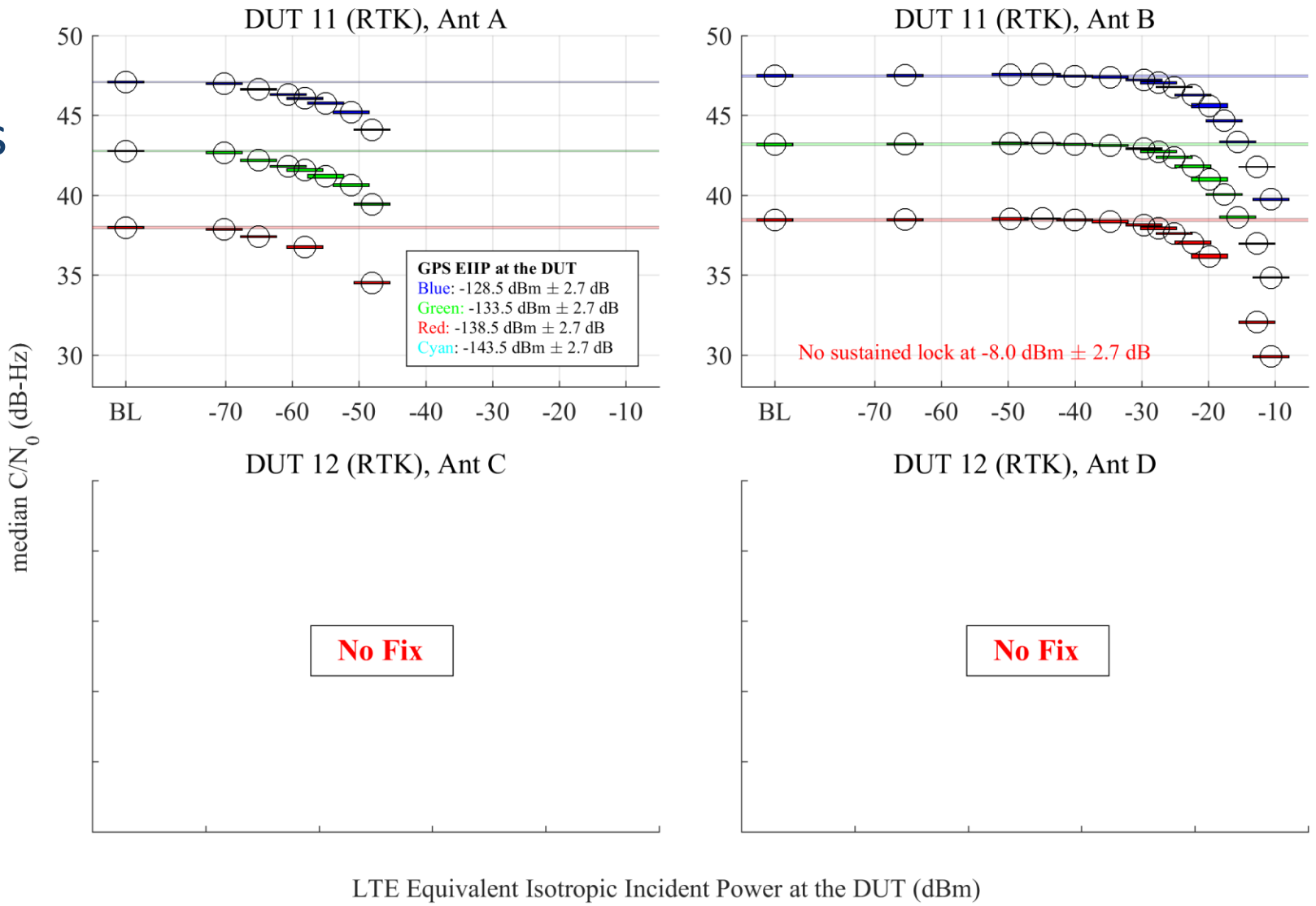
Fig. 6.136 – pg. 261

Real Time Kinematic

- 95% confidence regions for median C/N_0
- Uplink 1
- Limited satellite condition

-128.5 dBm	Baseline (BL) – No LTE Power
-133.5 dBm	Baseline (BL) – No LTE Power
-138.5 dBm	Baseline (BL) – No LTE Power
-143.5 dBm	Baseline (BL) – No LTE Power



NASCTN
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Fig. 6.135 – pg. 260

Real Time Kinematic

- 95% confidence regions for median 3D position error
- Uplink 1
- Limited satellite condition

Baseline (BL) – No LTE Power

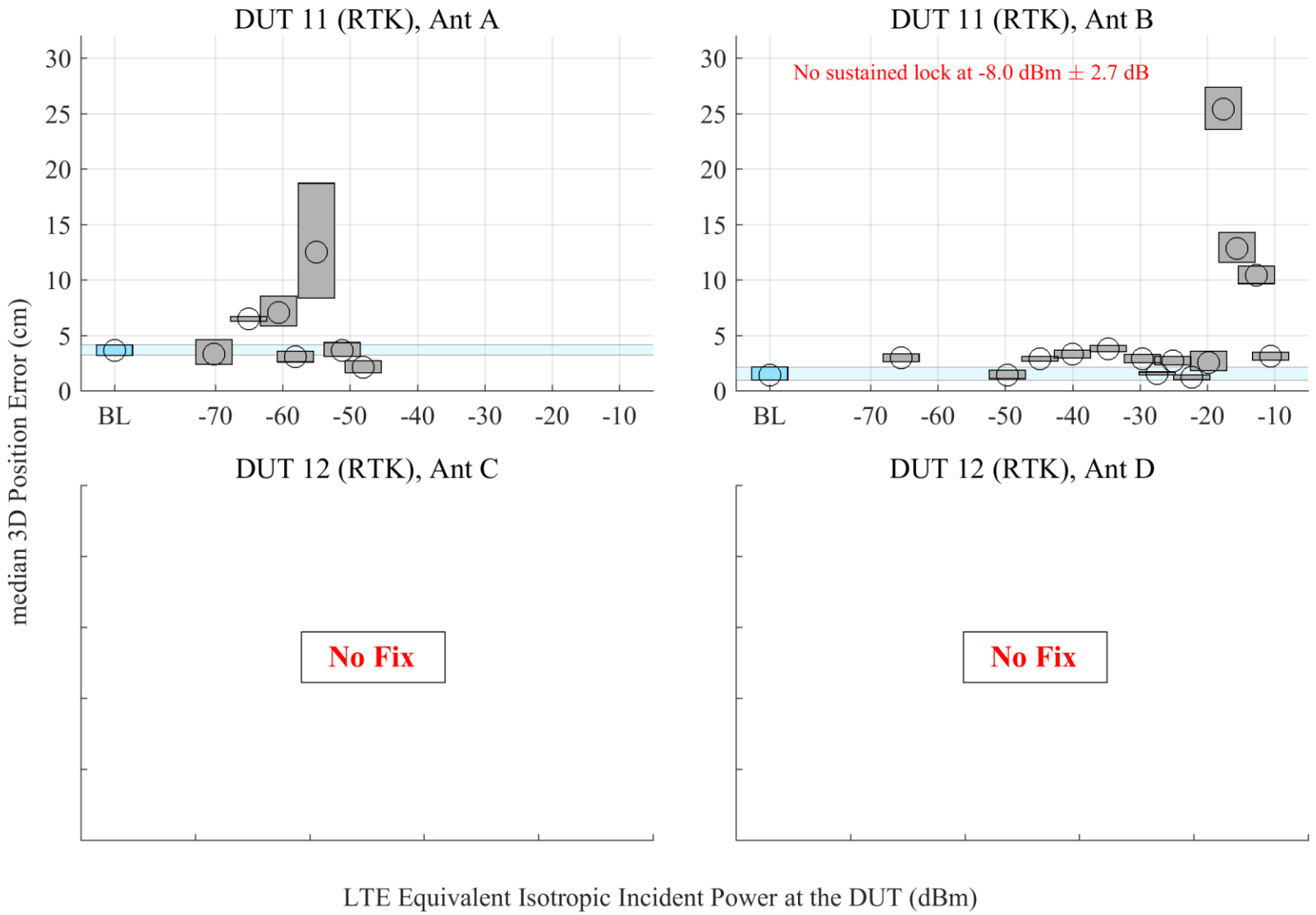

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Fig. 6.137 – pg. 262

Real Time Kinematic

- Number of reported satellites in view scatter plot
- Uplink 1
- Limited satellite condition

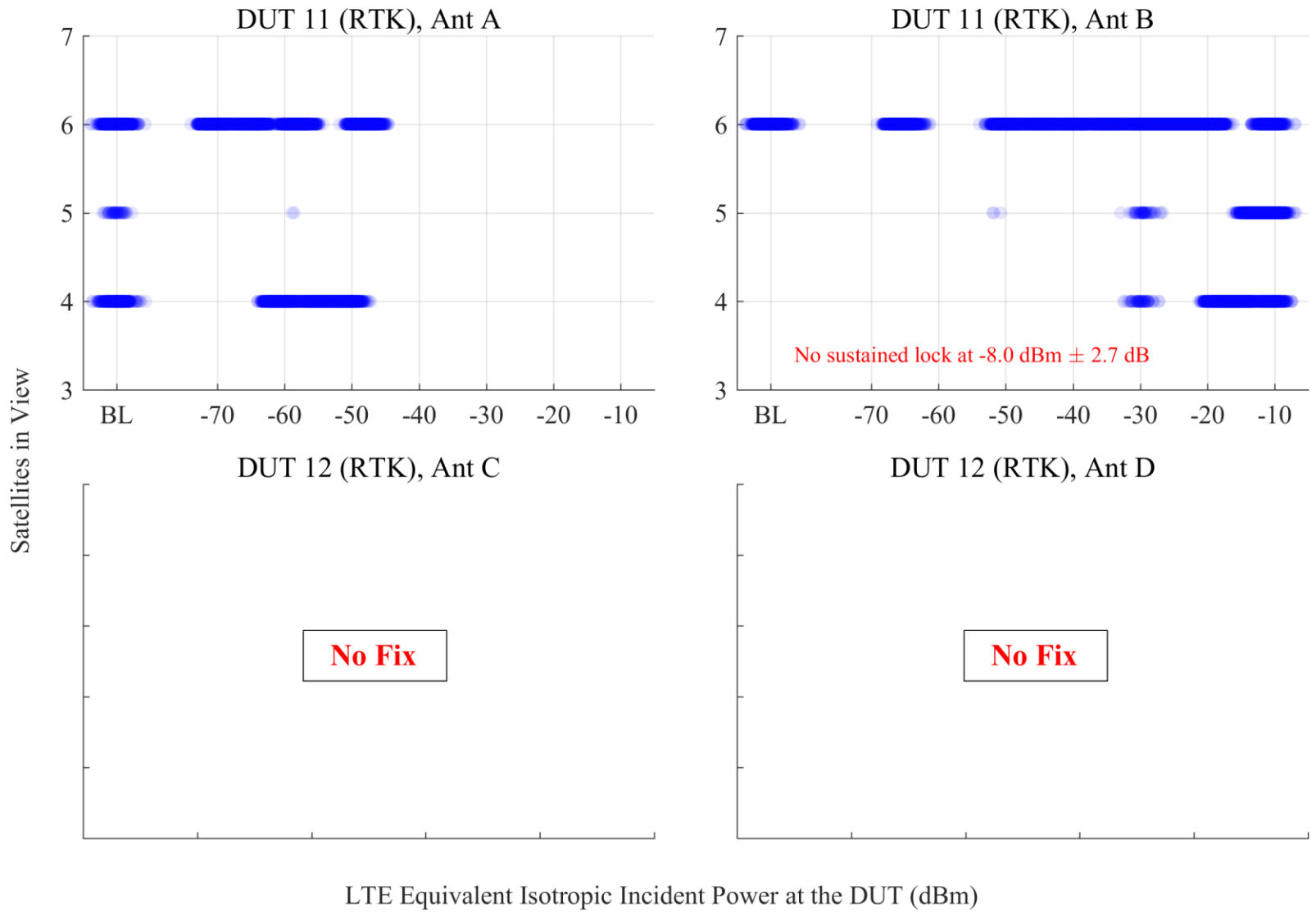

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Fig. 6.138 – pg. 263

Time To First Fix

General Navigation and Location

Precision Location

Real Time Kinematic

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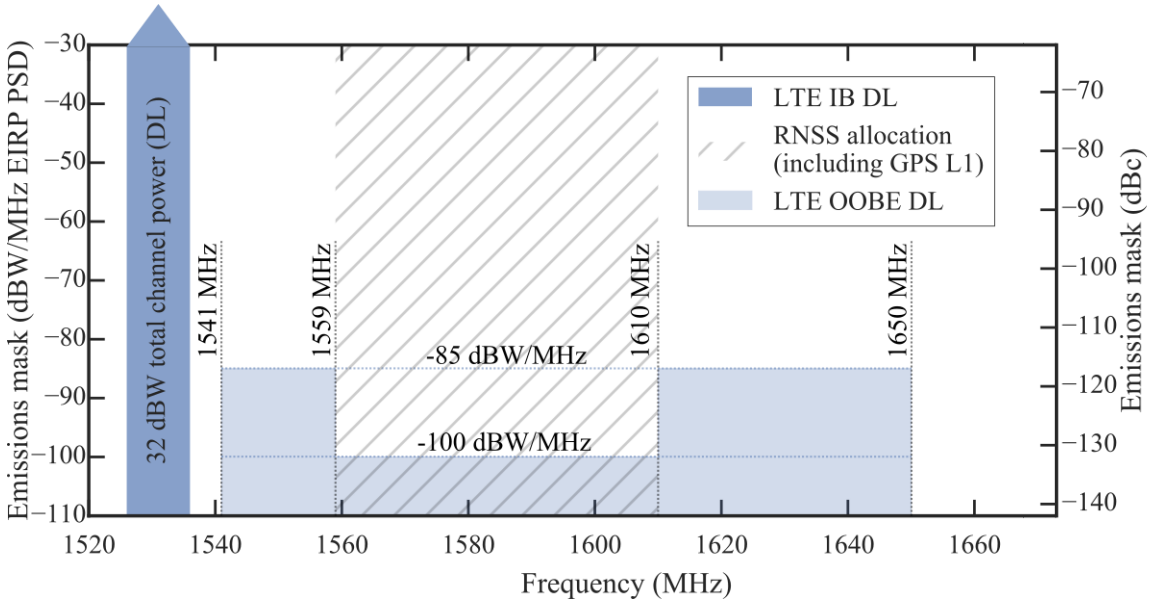
General Location and Navigation

- Nominal Satellite Condition
- TTFF
  - **Downlink**
  - Uplink 1



General Location

- TTFR (tunnel scenario)
- TTFR scatter plots
- Downlink
- Nominal satellite condition
- 100 trials

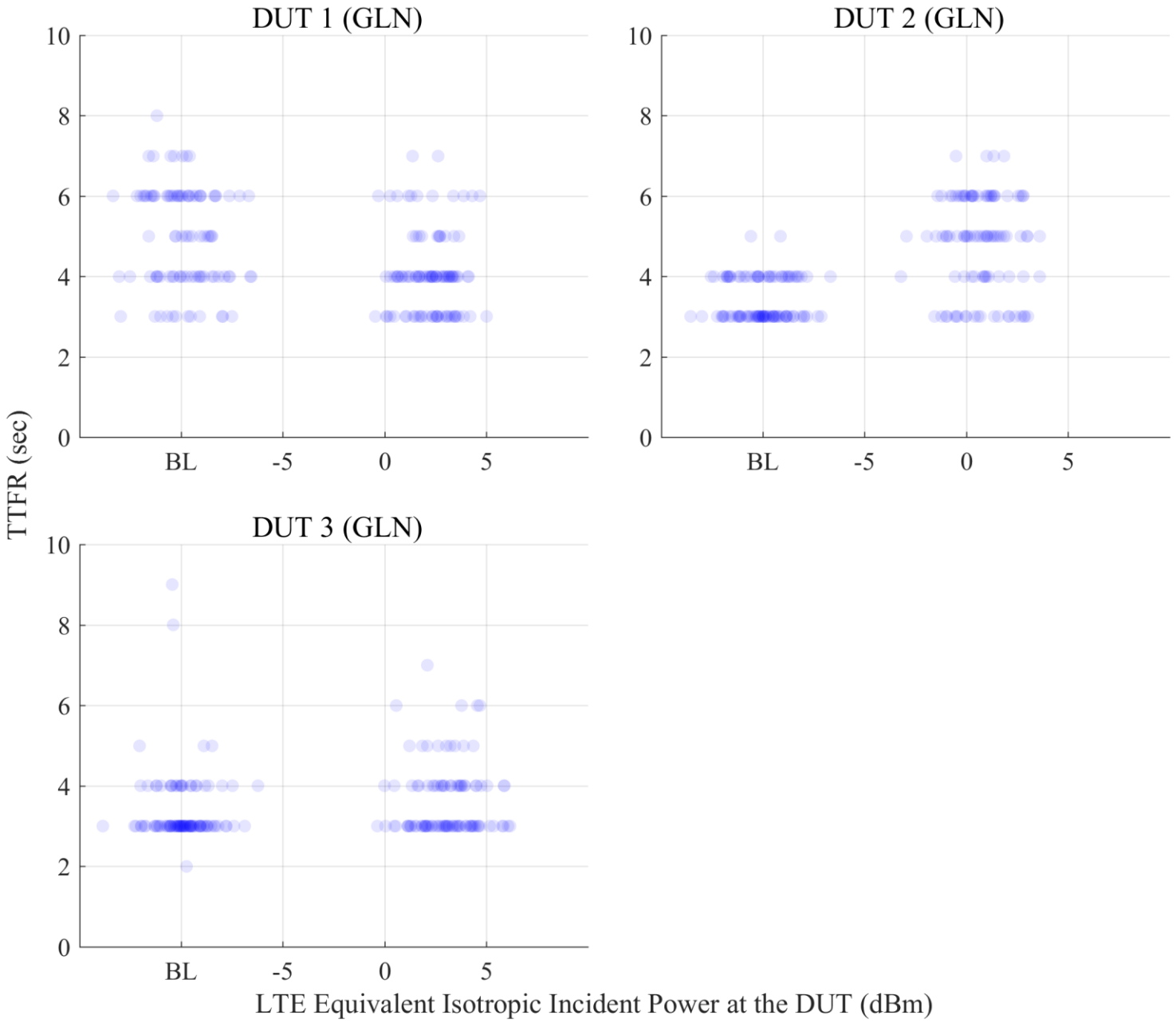


Fig. 6.98 – pg. 222

General Location

- TTFR (tunnel scenario)
- Empirical estimates of the CDF
- Downlink
- Nominal satellite condition

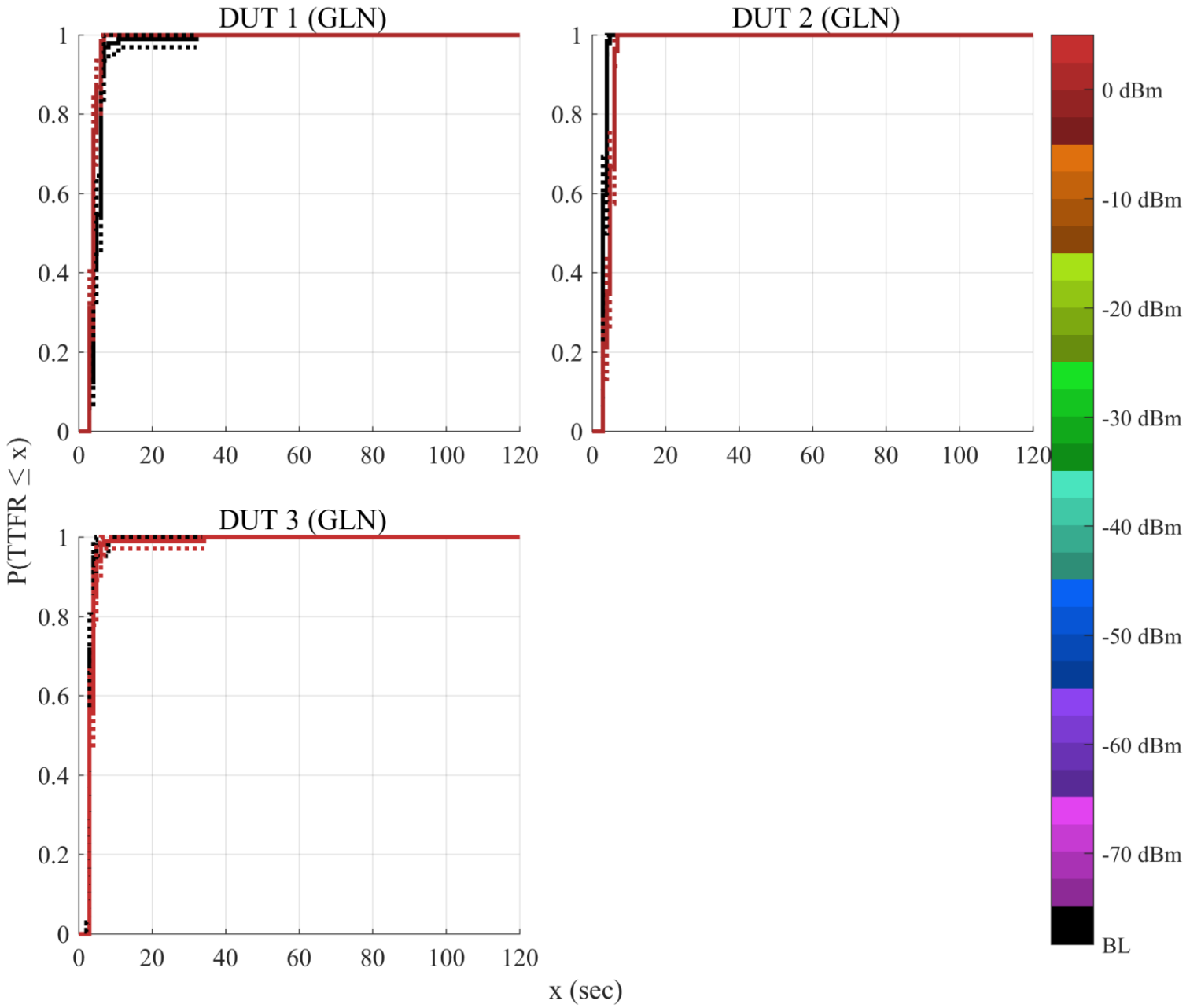
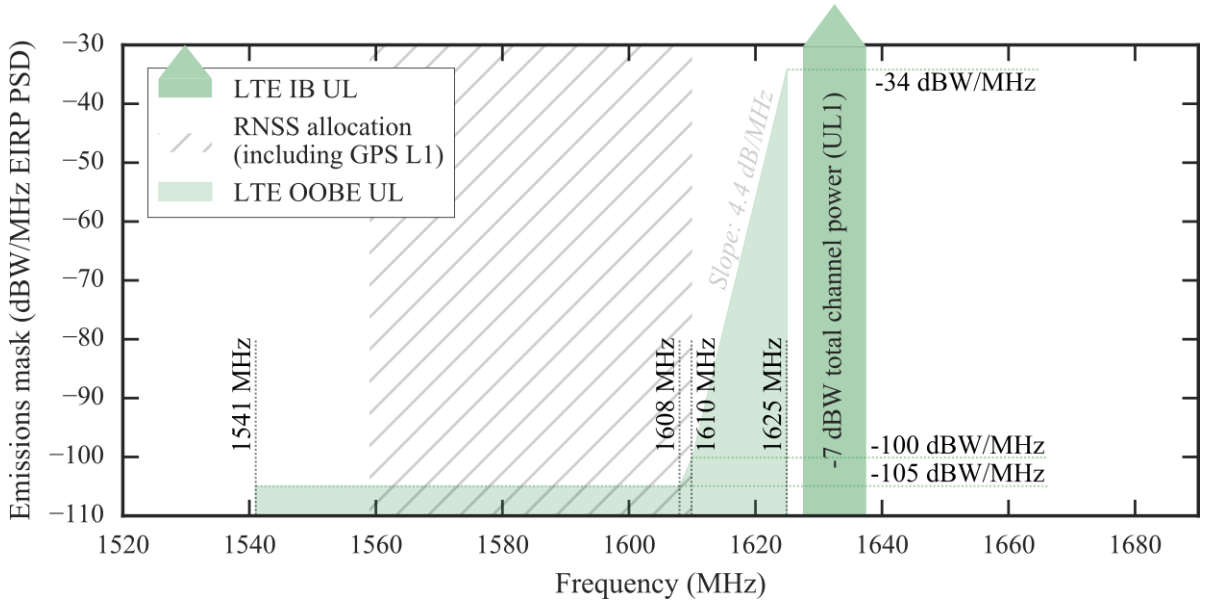


Fig. 6.97 – pg. 221

General Location and Navigation

- Nominal Satellite Condition
- TTFF
  - Downlink
  - **Uplink 1**



General Location

- TTFR (tunnel scenario)
- TTFR scatter plots
- Uplink 1
- Nominal satellite condition
- 100 trials

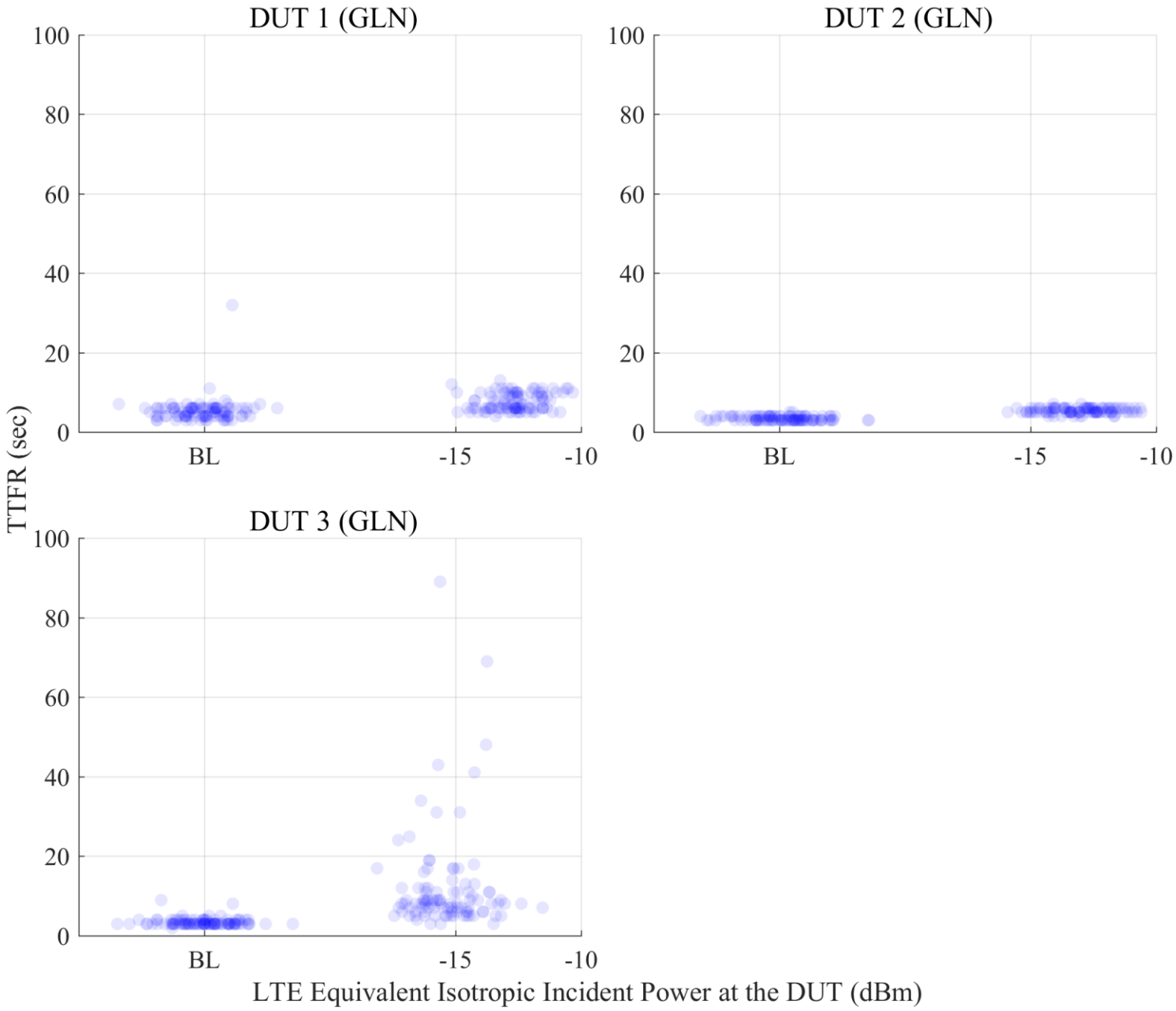


Fig. 6.104 – pg. 228

General Location

- TTFR (tunnel scenario)
- Empirical estimates of the CDF
- Uplink 1
- Nominal satellite condition

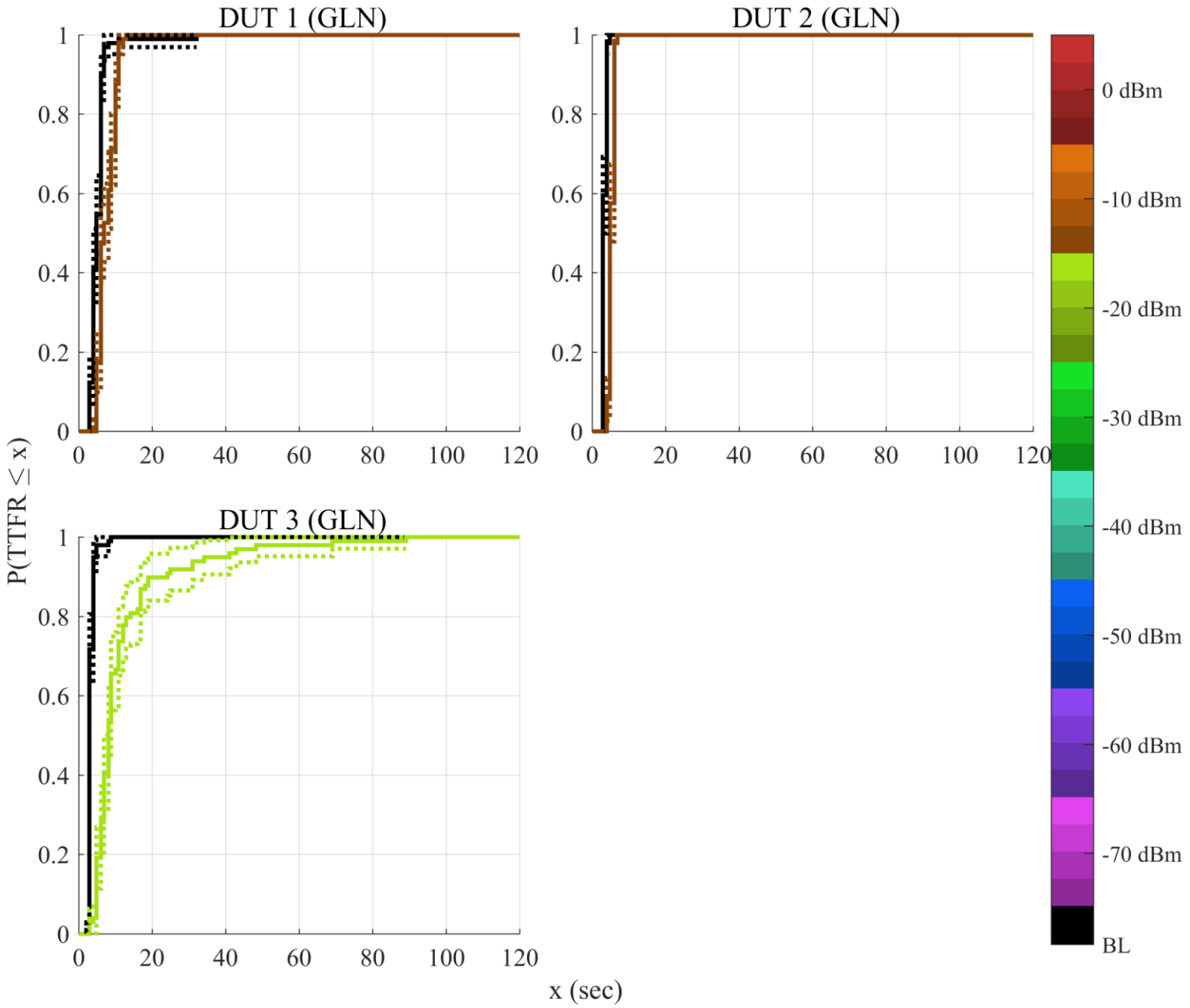
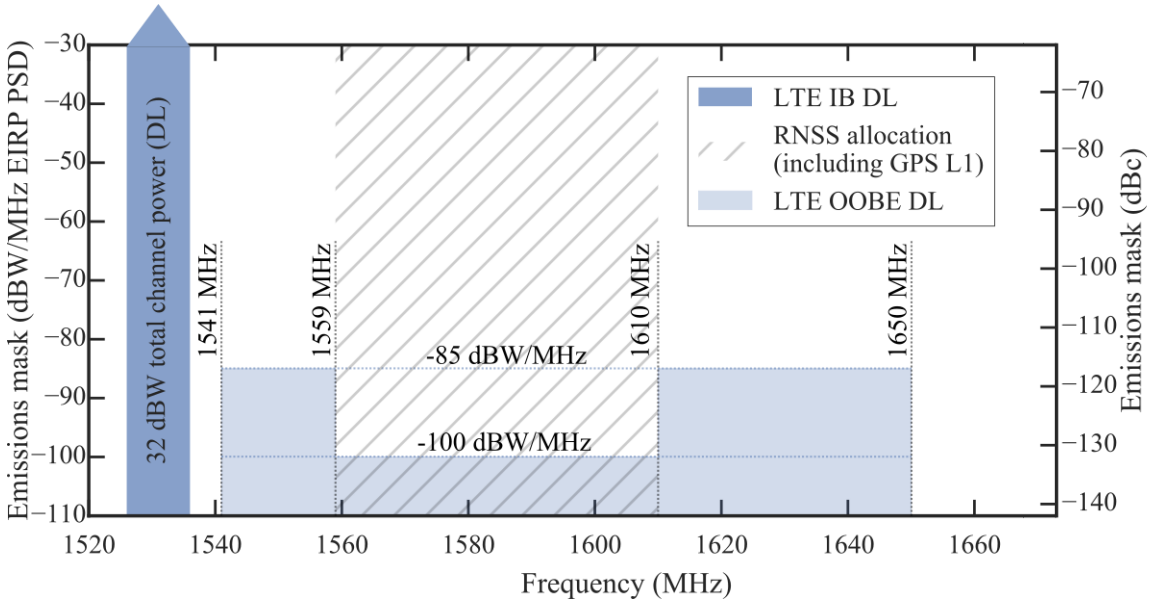


Fig. 6.103 – pg. 227

Precision Location

- Nominal Satellite Condition
- TTFF
  - **Downlink**
  - Uplink 1



Precision Location

- TTFF (Cold-Start)
- TTFF scatter plots
- Downlink
- Nominal satellite condition
- 100 trials

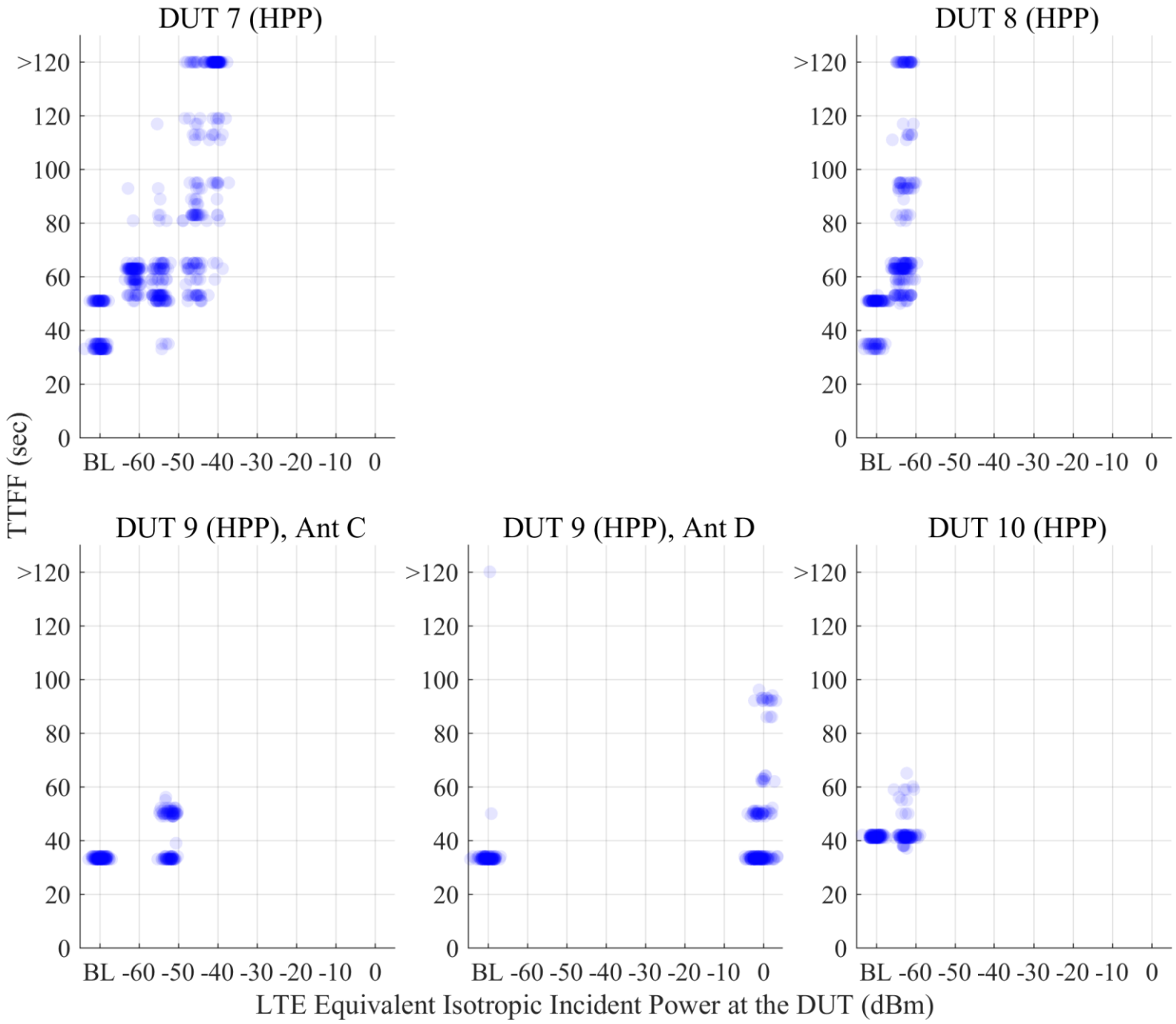


Fig. 6.100 – pg. 224

Precision Location

- TTFF (Cold-Start)
- Empirical estimates of the CDF
- Downlink
- Nominal satellite condition

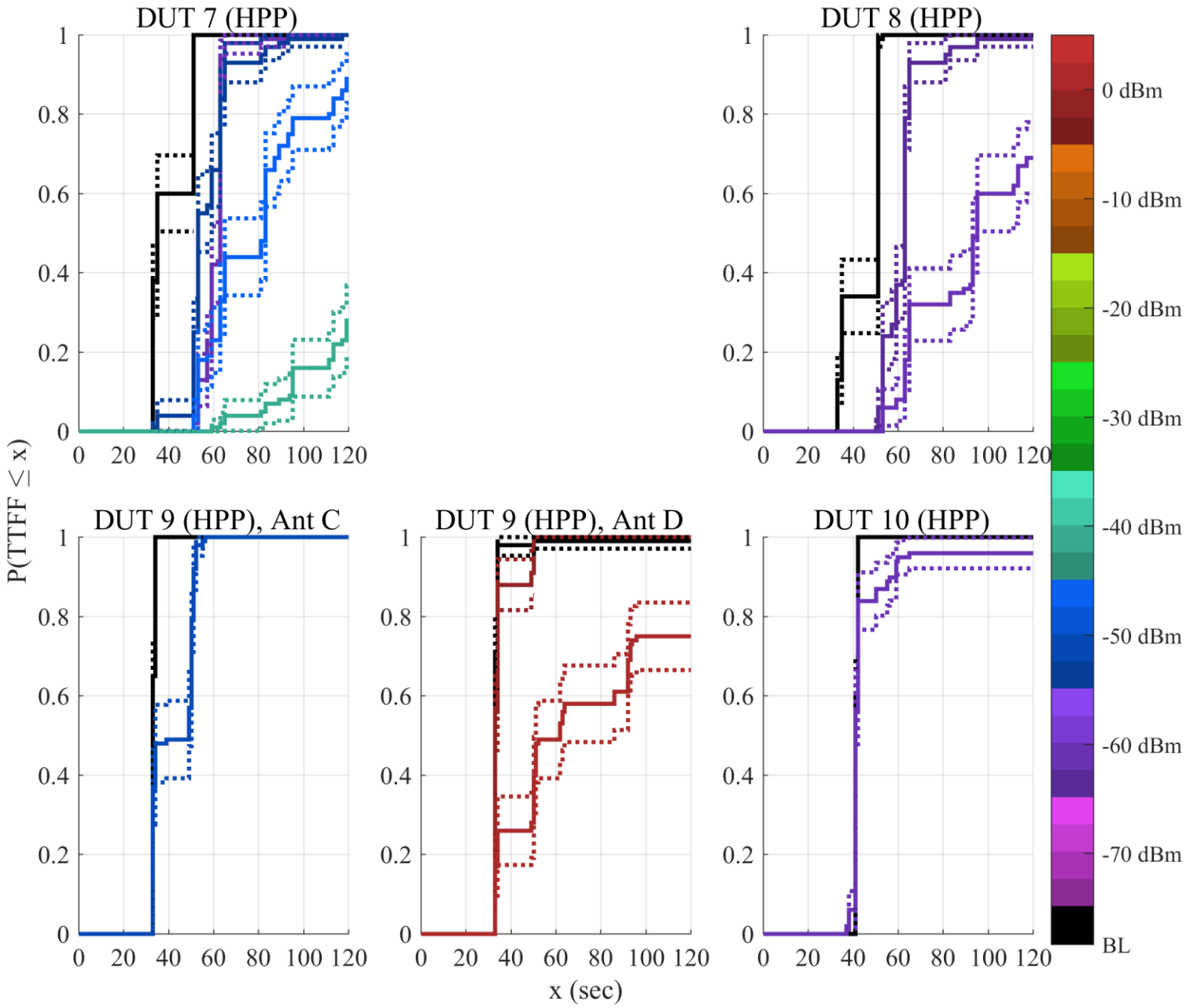
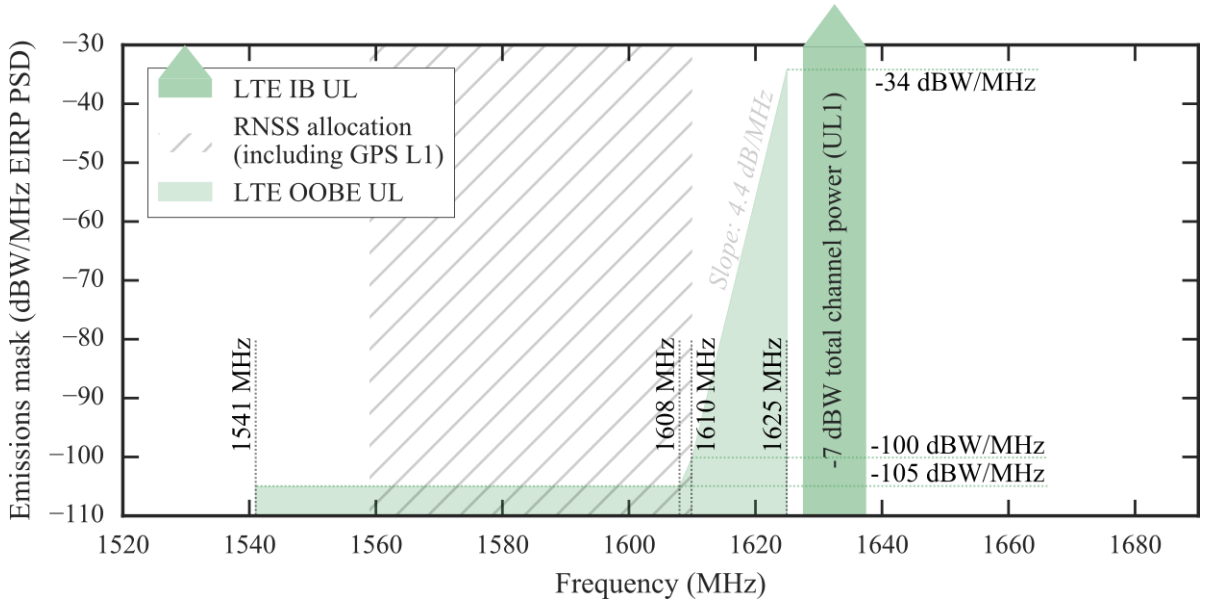


Fig. 6.99 – pg. 223

Precision Location

- Nominal Satellite Condition
- TTFF
  - Downlink
  - **Uplink 1**



Precision Location

- TTFF (Cold-Start)
- TTFF scatter plots
- Uplink 1
- Nominal satellite condition
- 100 trials

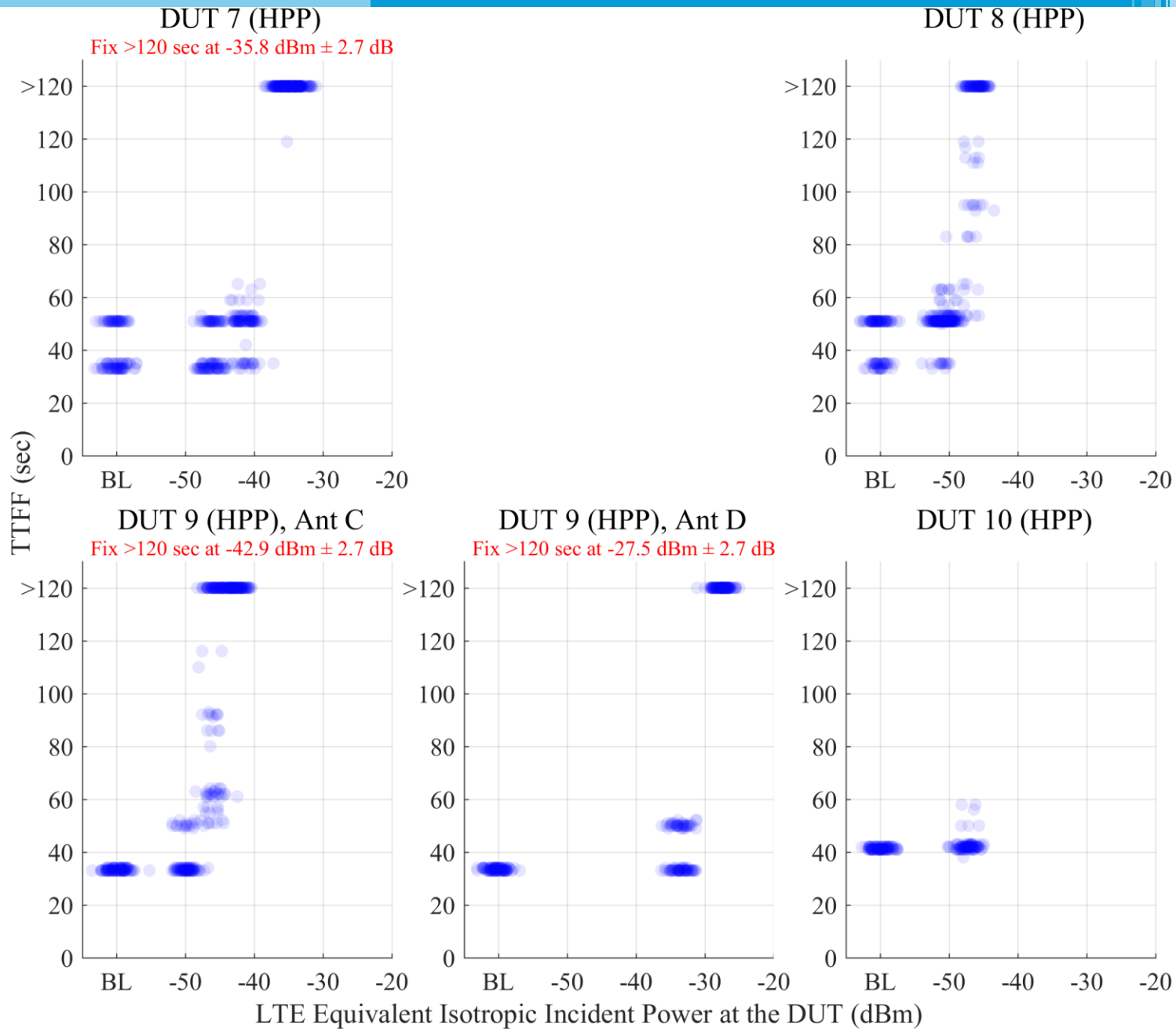


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Fig. 6.106 – pg. 230

Precision Location

- TTFF (Cold-Start)
- Empirical estimates of the CDF
- Uplink 1
- Nominal satellite condition

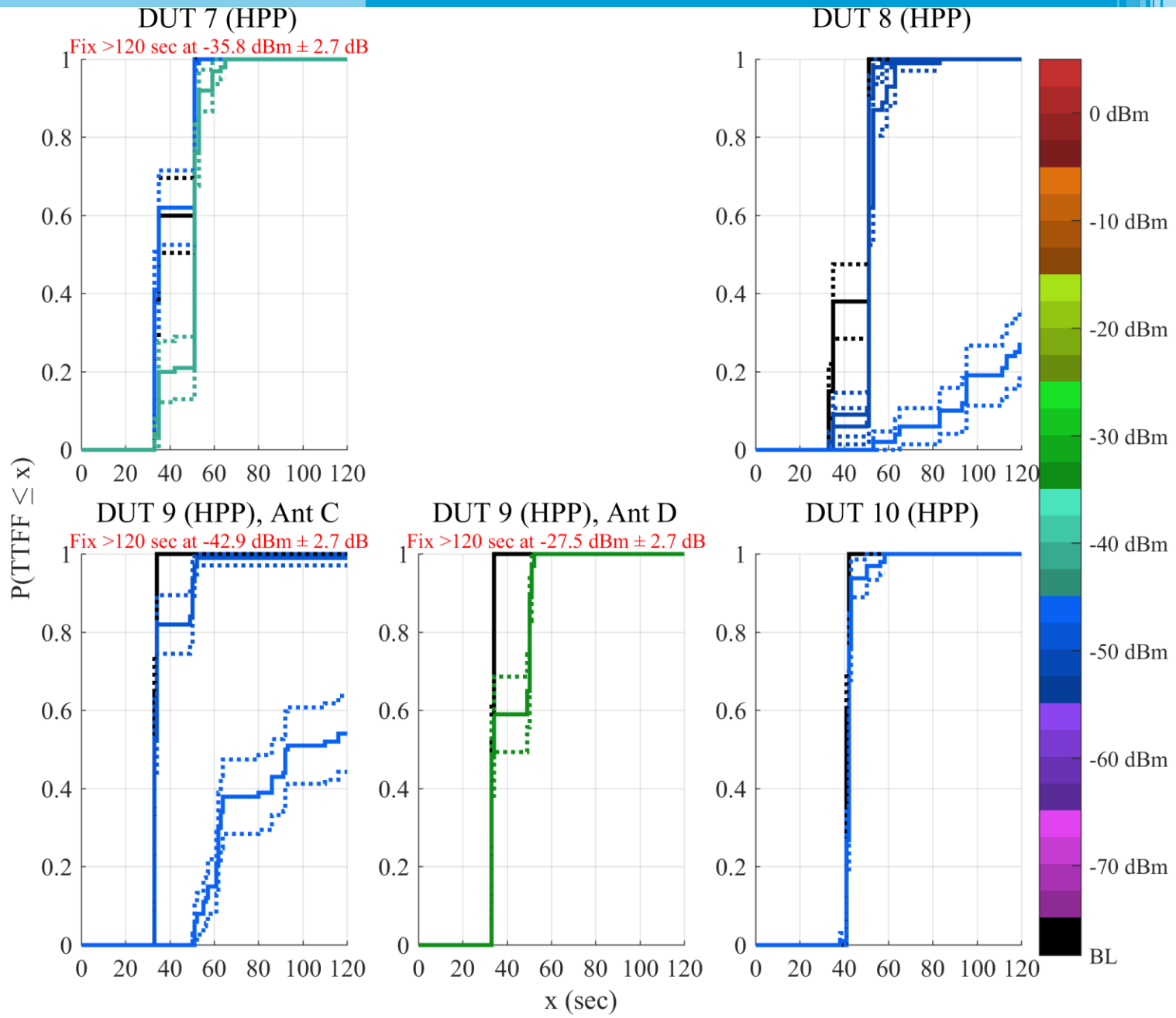
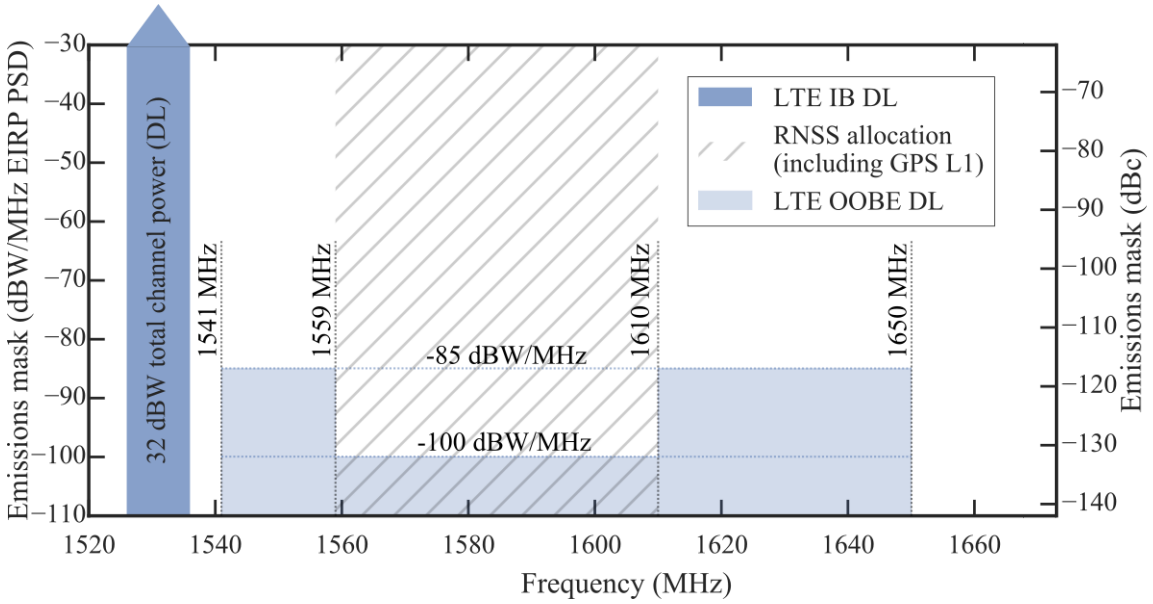


Fig. 6.105 – pg. 229

Real Time Kinematic

- Nominal Satellite Condition
- TTFF
  - **Downlink**
  - Uplink 1



Real Time Kinematic

- TTFF (Cold-Start)
- TTFF scatter plots
- Downlink
- Nominal satellite condition
- 100 trials

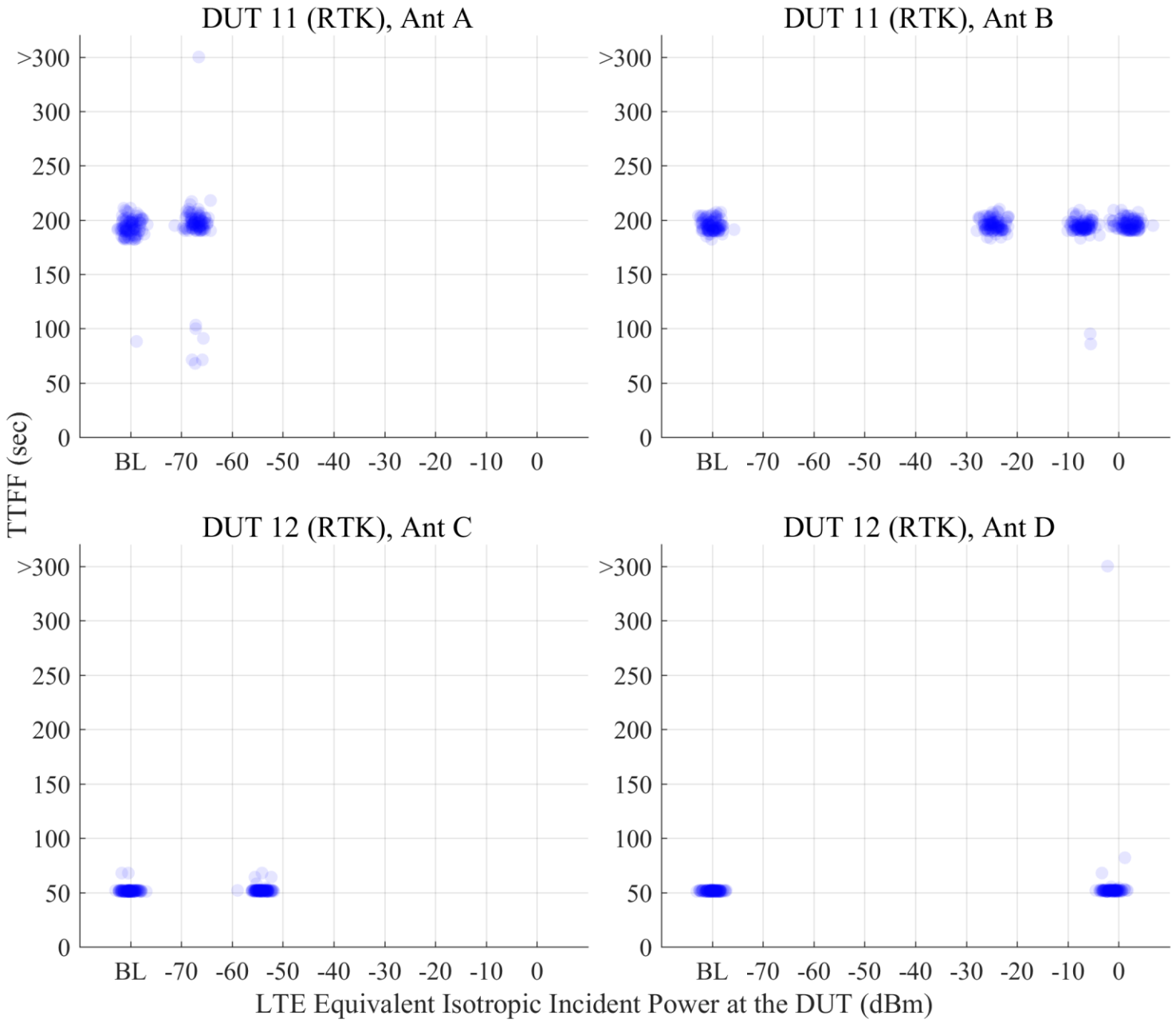


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Fig. 6.108 – pg. 232

Real Time Kinematic

- TTFF (Cold-Start)
- Empirical estimates of the CDF
- Downlink
- Nominal satellite condition

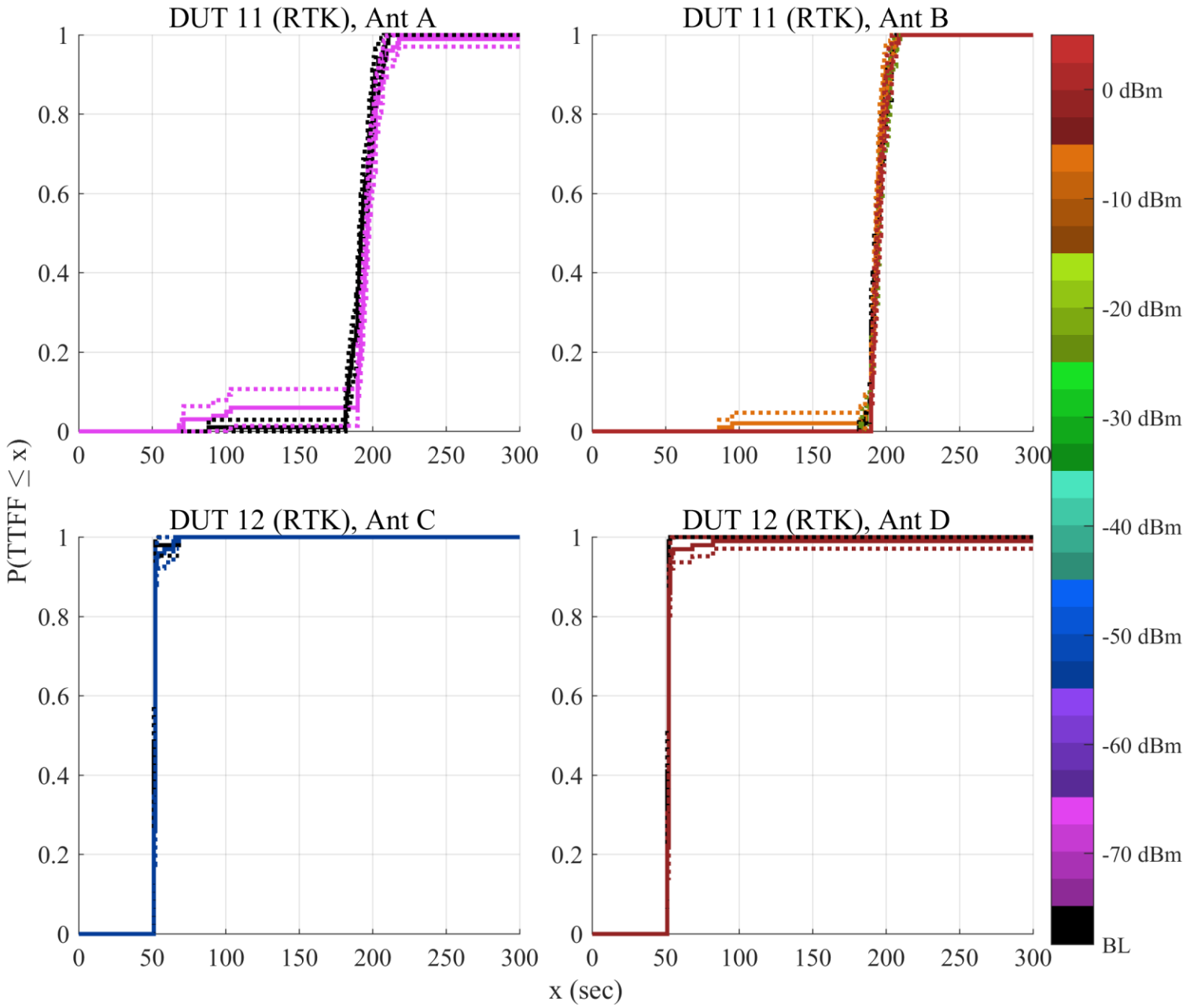
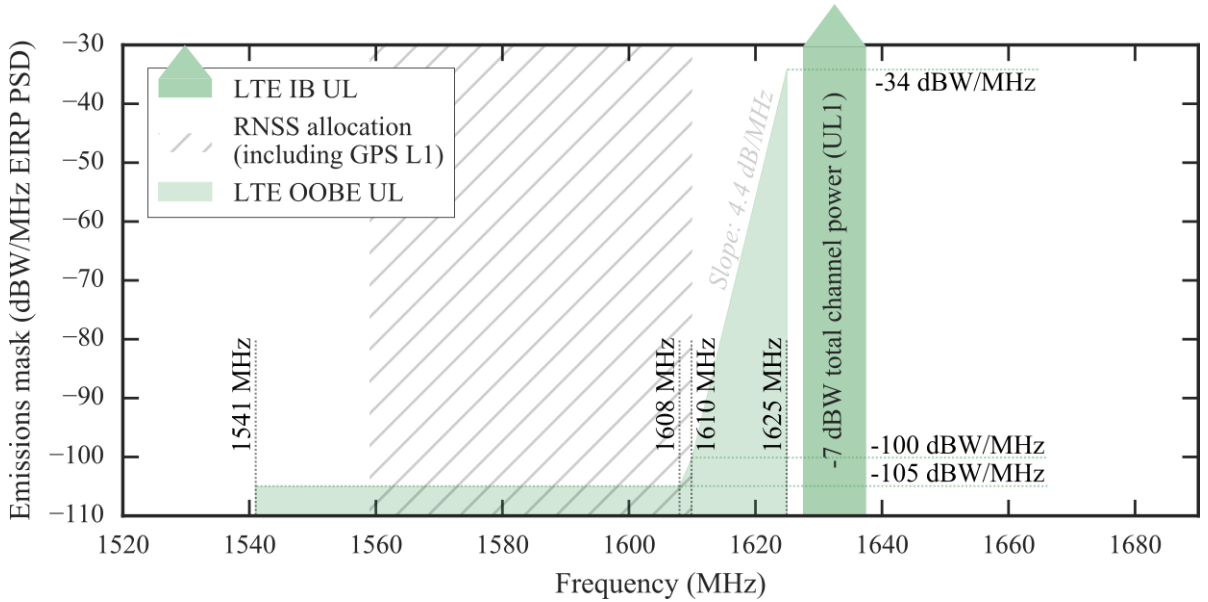


Fig. 6.107 – pg. 231

Real Time Kinematic

- Nominal Satellite Condition
- TTFF
  - Downlink
  - **Uplink 1**



Real Time Kinematic

- TTFF (Cold-Start)
- TTFF scatter plots
- Uplink 1
- Nominal satellite condition
- 100 trials

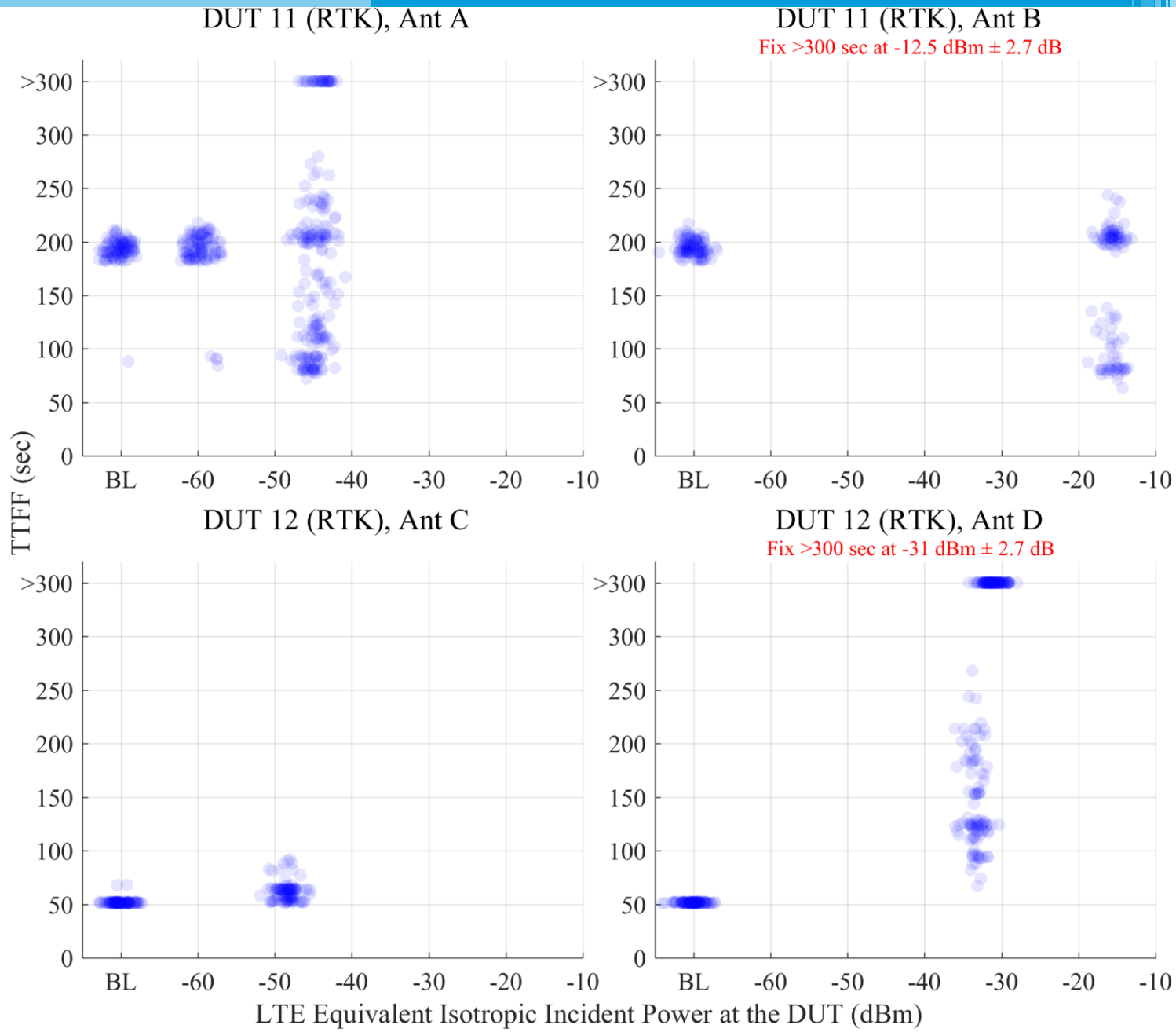


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Fig. 6.102 – pg. 226

Real Time Kinematic

- TTFF (Cold-Start)
- Empirical estimates of the CDF
- Uplink 1
- Nominal satellite condition

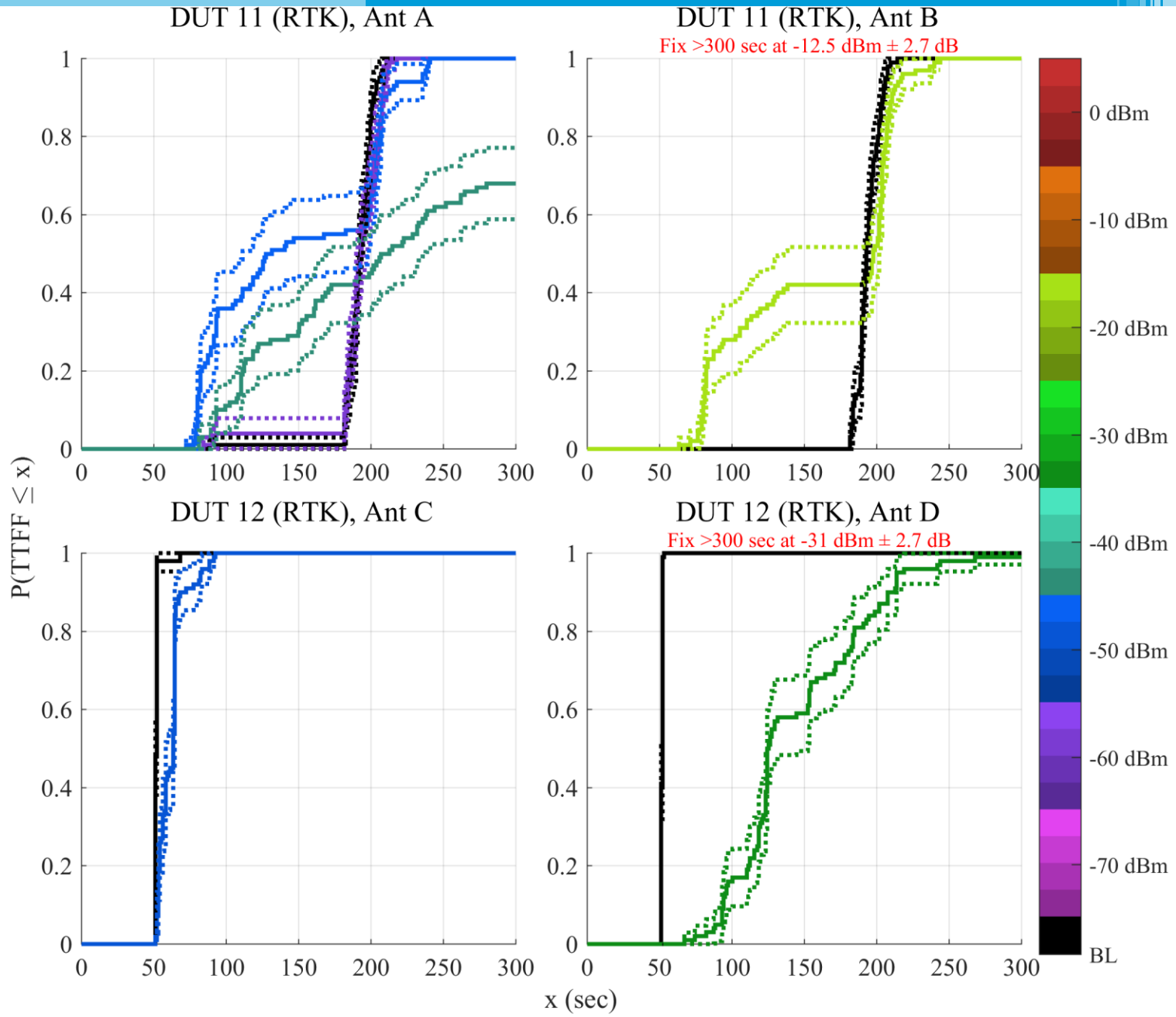
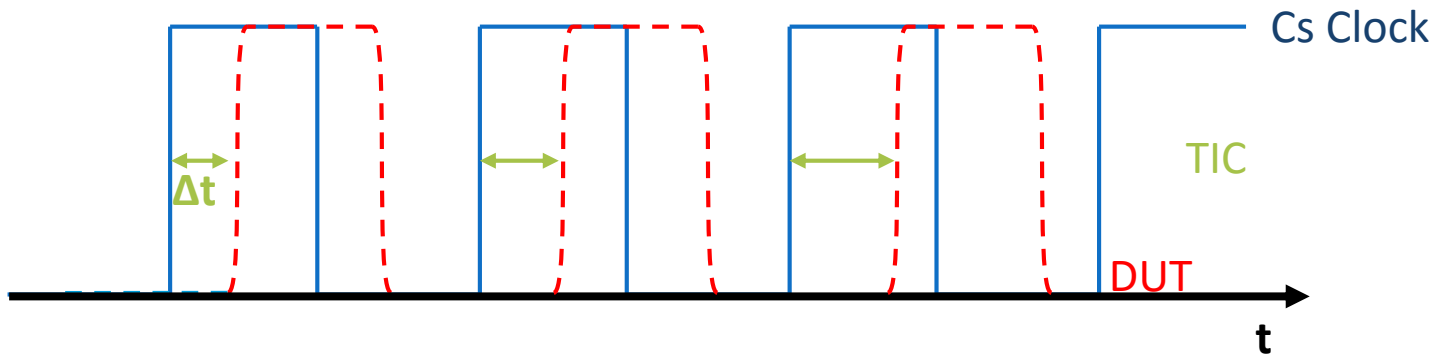


Fig. 6.101 – pg. 225

TIMING DEVICES



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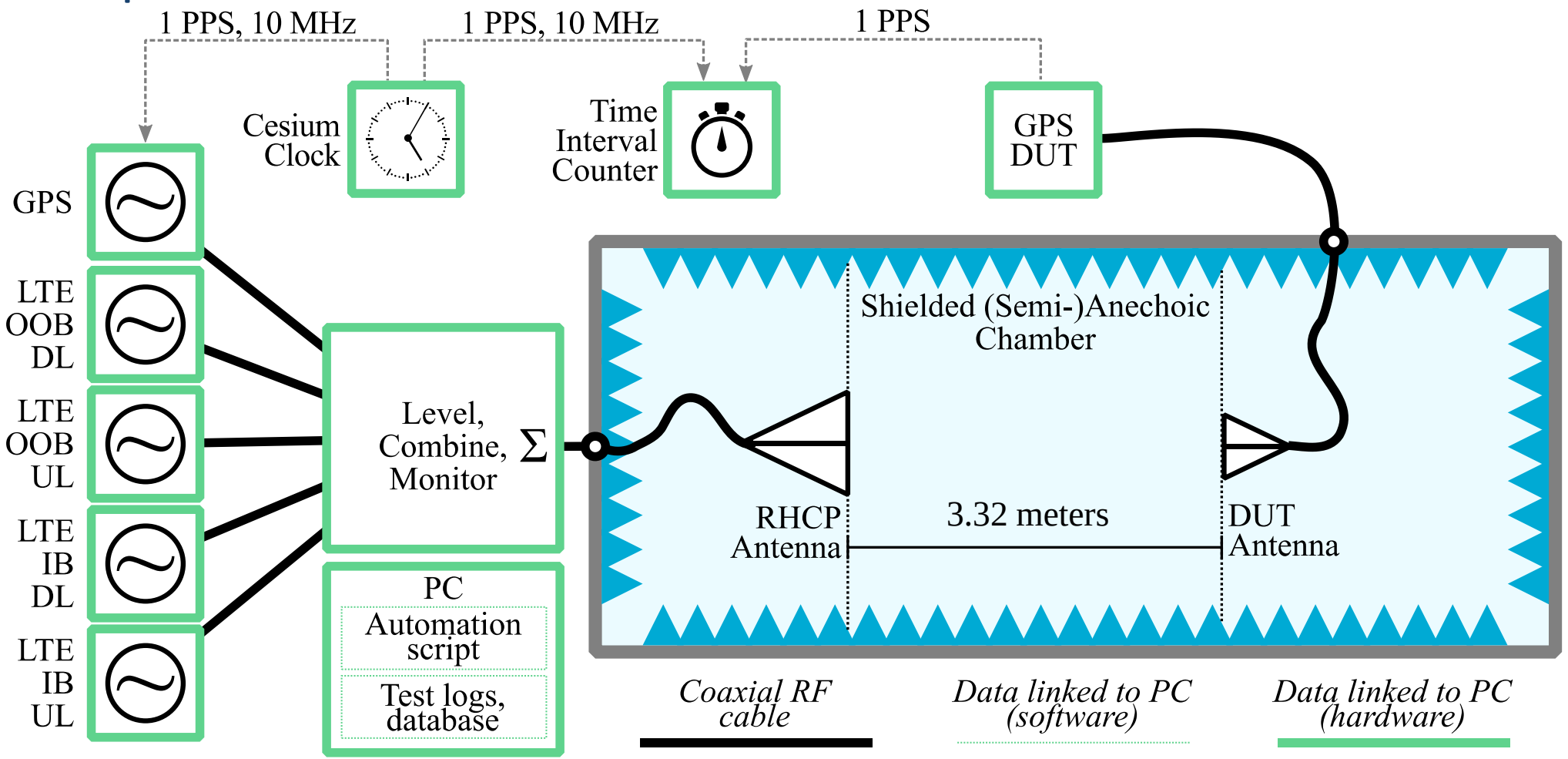
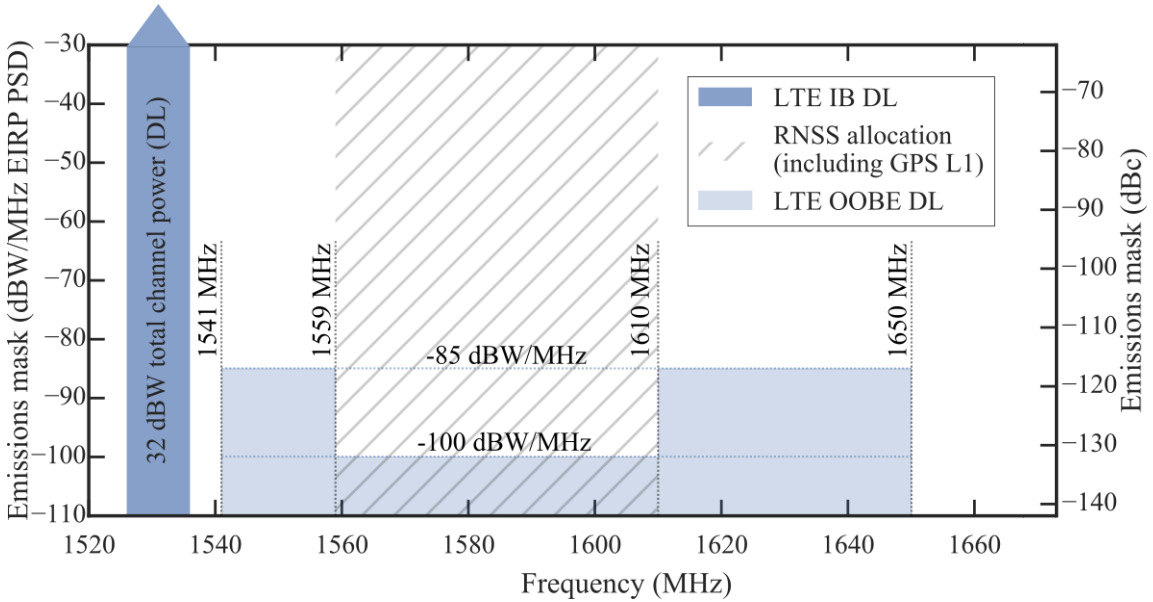
Timing Setup



Timing

- Nominal Satellite Condition
- Timing
  - **Downlink**
  - Uplink 1
  - Uplink 2
  - Combo DL + UL1



Timing

- C/N0 scatter plots (top)
- 95% confidence regions for median C/N_0 (bottom)
- Downlink
- Nominal satellite condition

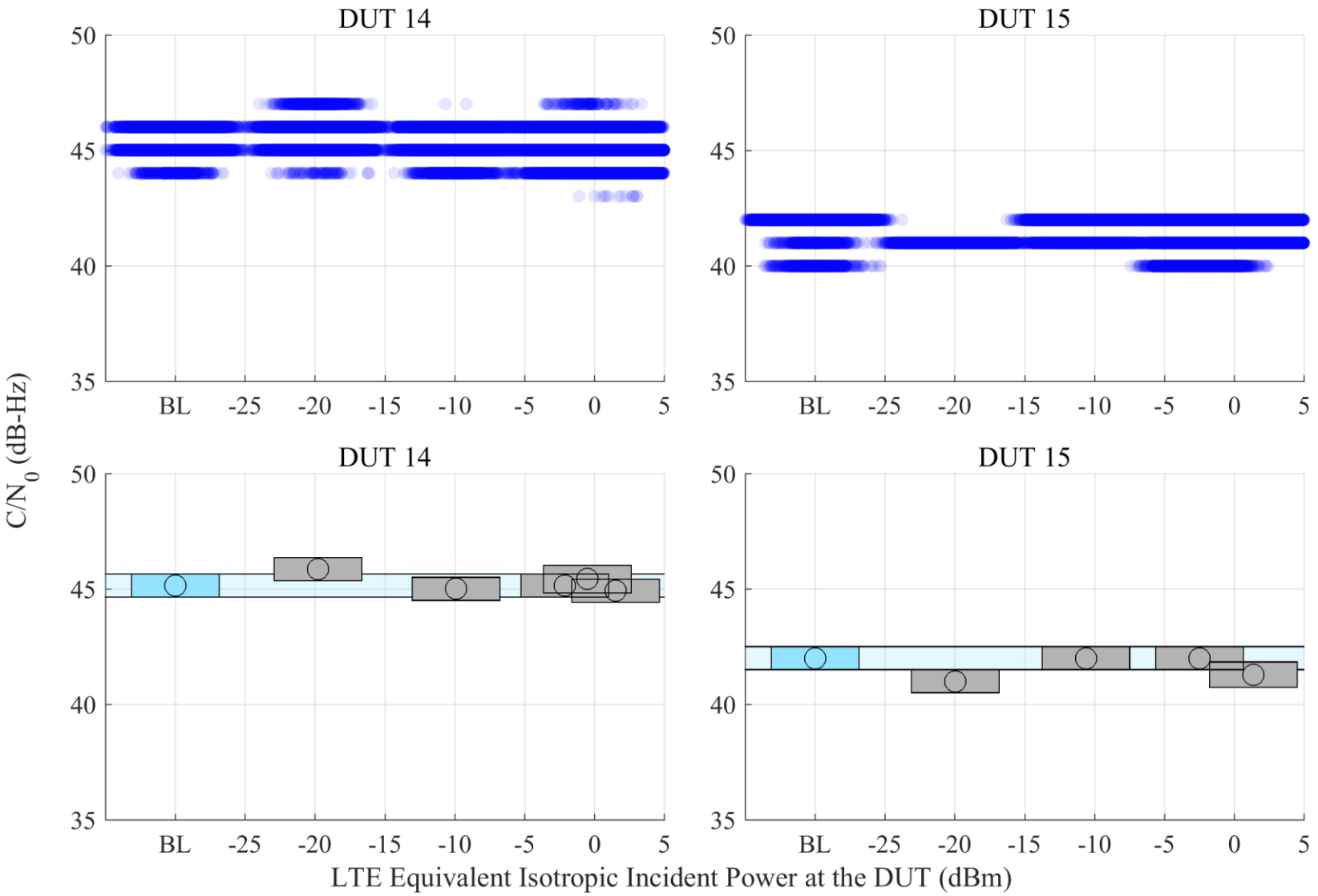


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Fig. 6.74 – pg. 196

Timing

- $\Delta T = PPS_{CSClock} - PPS_{DUT}$
- TIC data after Warm-up estimation
- Downlink
- Nominal satellite condition

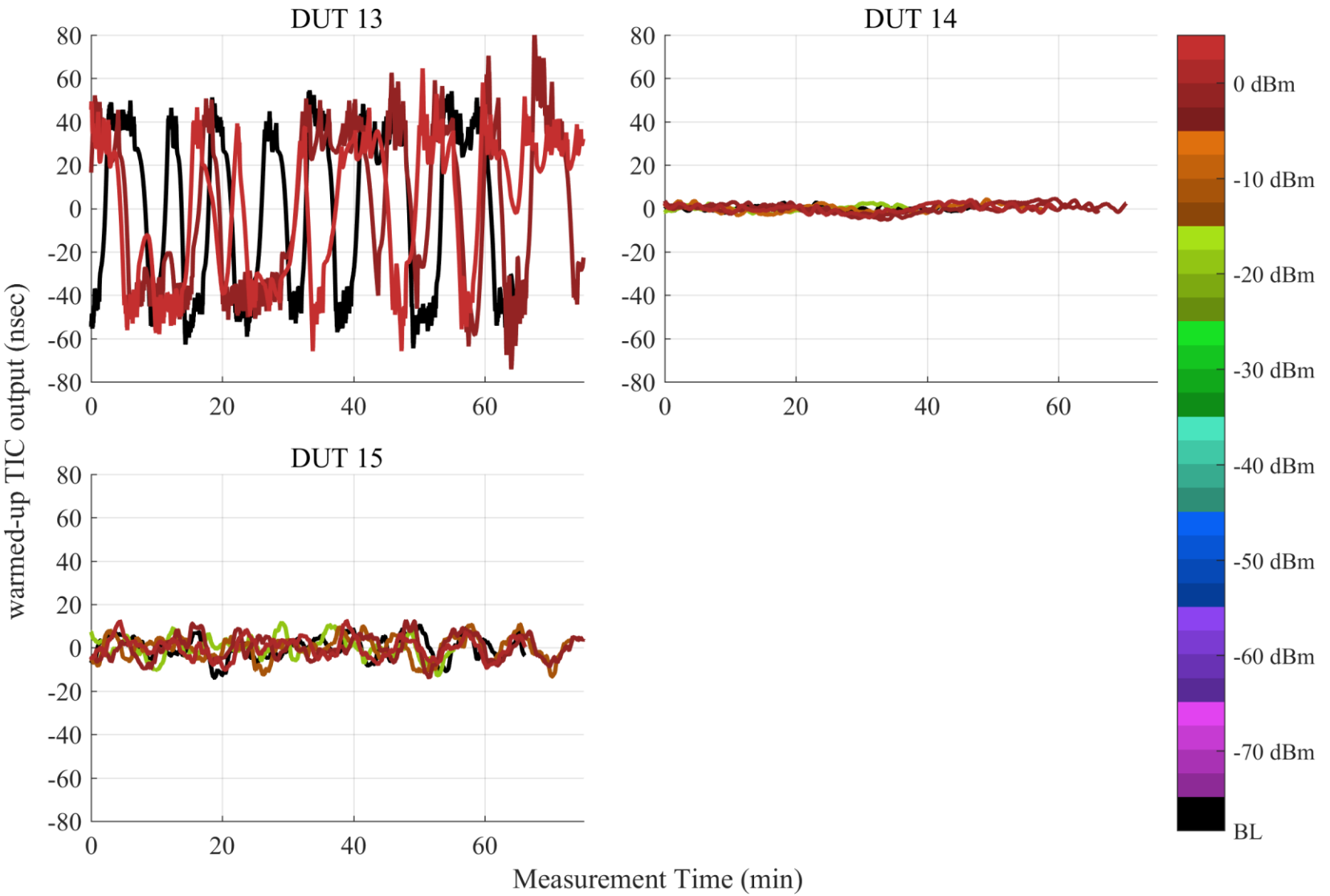

Fig. 6.69 – pg. 191

Timing

- Allan Time Deviation Estimate from ΔT after Warm-up time
- Downlink
- Nominal satellite condition

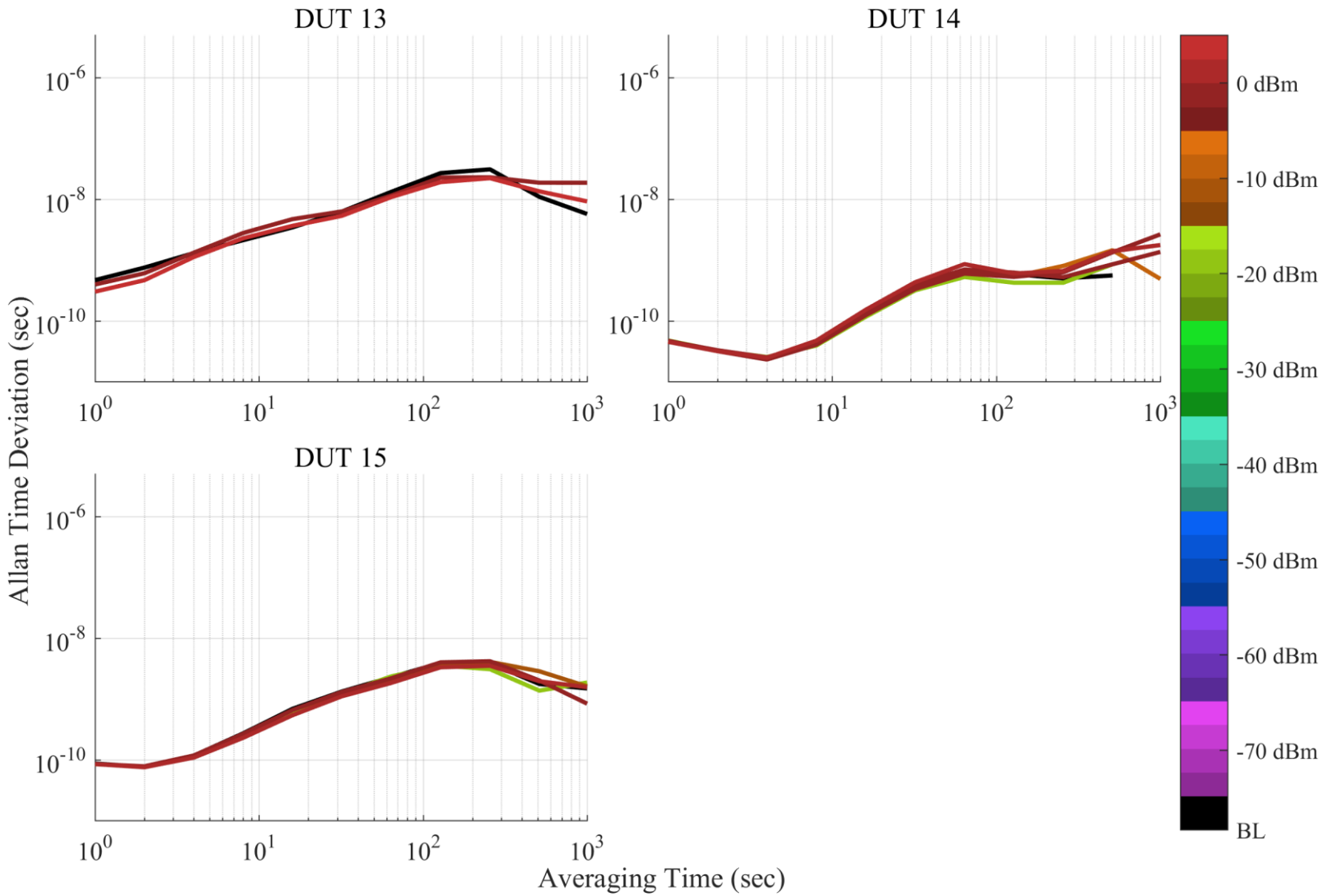

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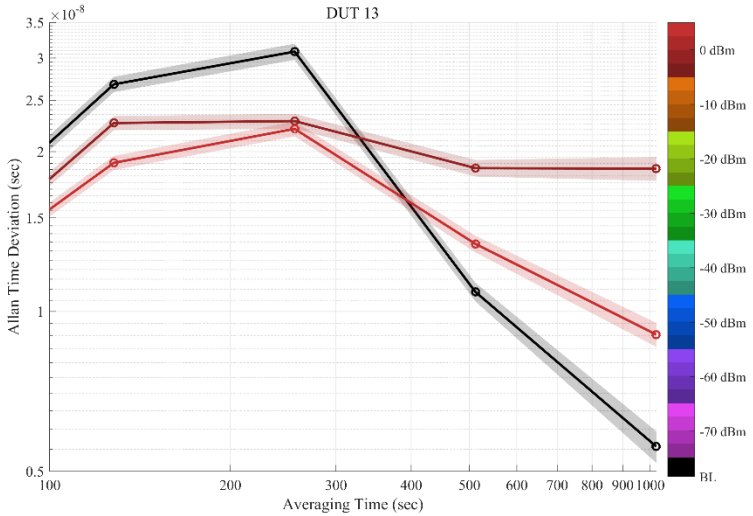
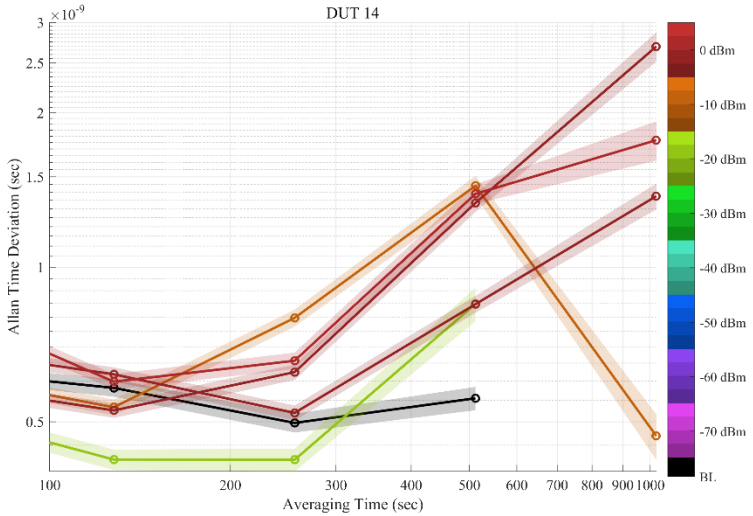
Fig. 6.70 – pg. 192

Zoomed TDEV





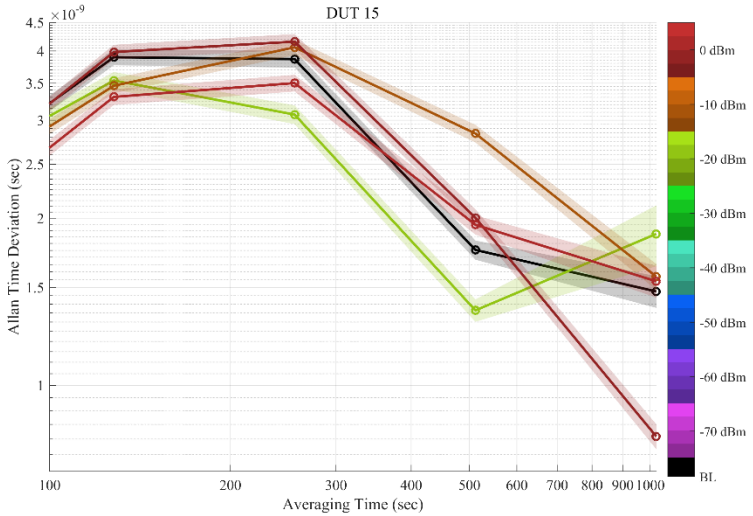


Fig. 6.71 – pg. 193

Fig. 6.72 – pg. 194

Fig. 6.73 – pg. 195

Timing

- Number of reported satellites in view scatter plot
- Downlink
- Nominal satellite condition

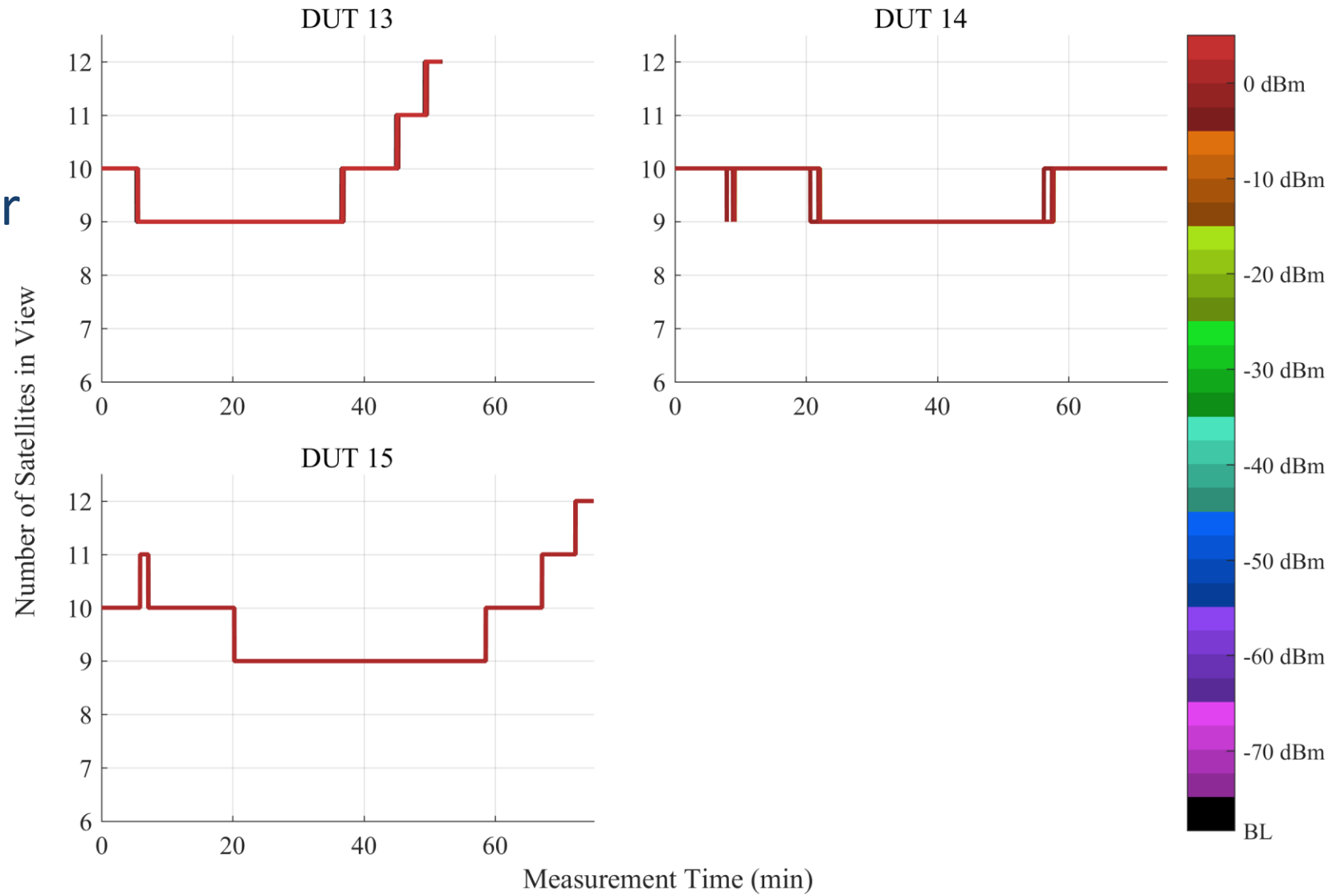


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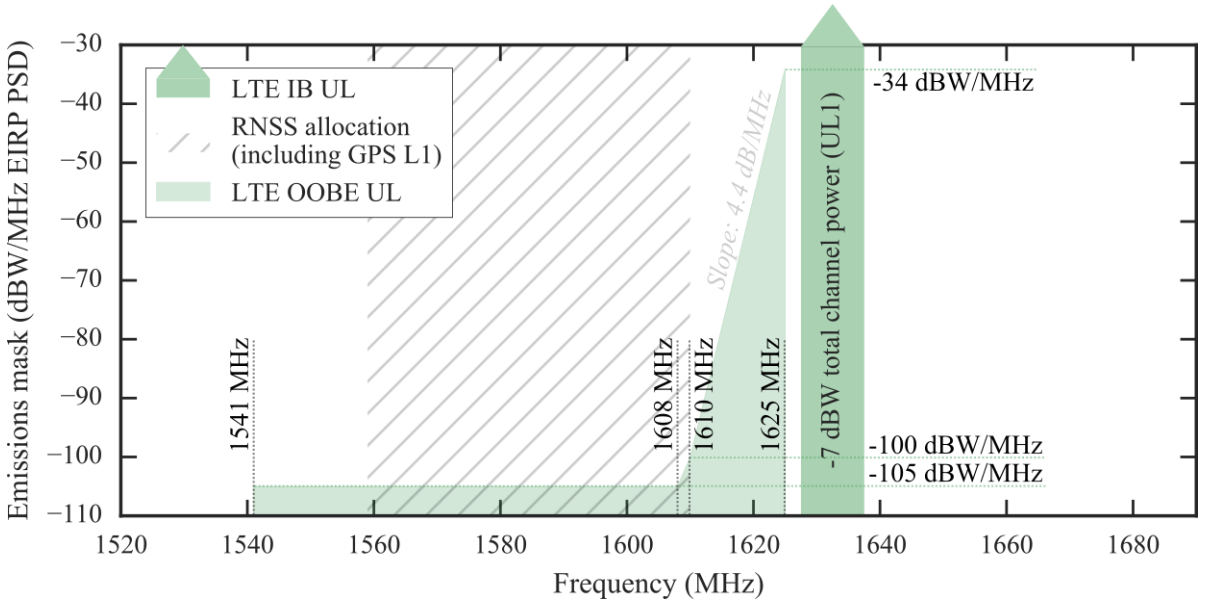
Fig. 6.75 – pg. 197

Timing

- Nominal Satellite Condition
- Timing
  - Downlink
  - **Uplink 1**
  - Uplink 2
  - Combo DL + UL1



Timing

- C/N0 scatter plots (top)
- 95% confidence regions for median C/N_0 (bottom)
- Uplink 1
- Nominal satellite condition

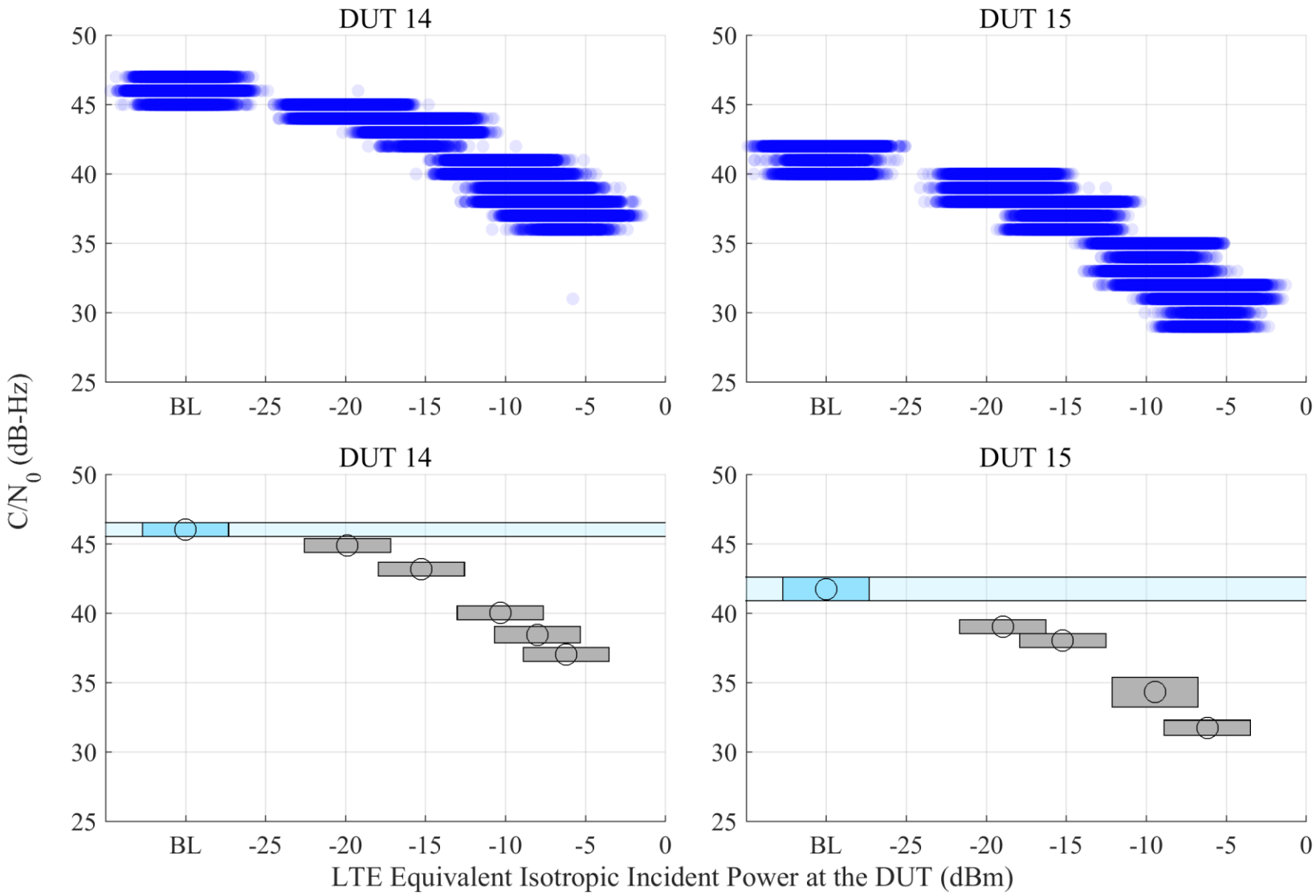


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Fig. 6.81 – pg. 203

Timing

- $\Delta T = PPS_{CSClock} - PPS_{DUT}$
- TIC data after Warm-up estimation
- Uplink 1
- Nominal satellite condition

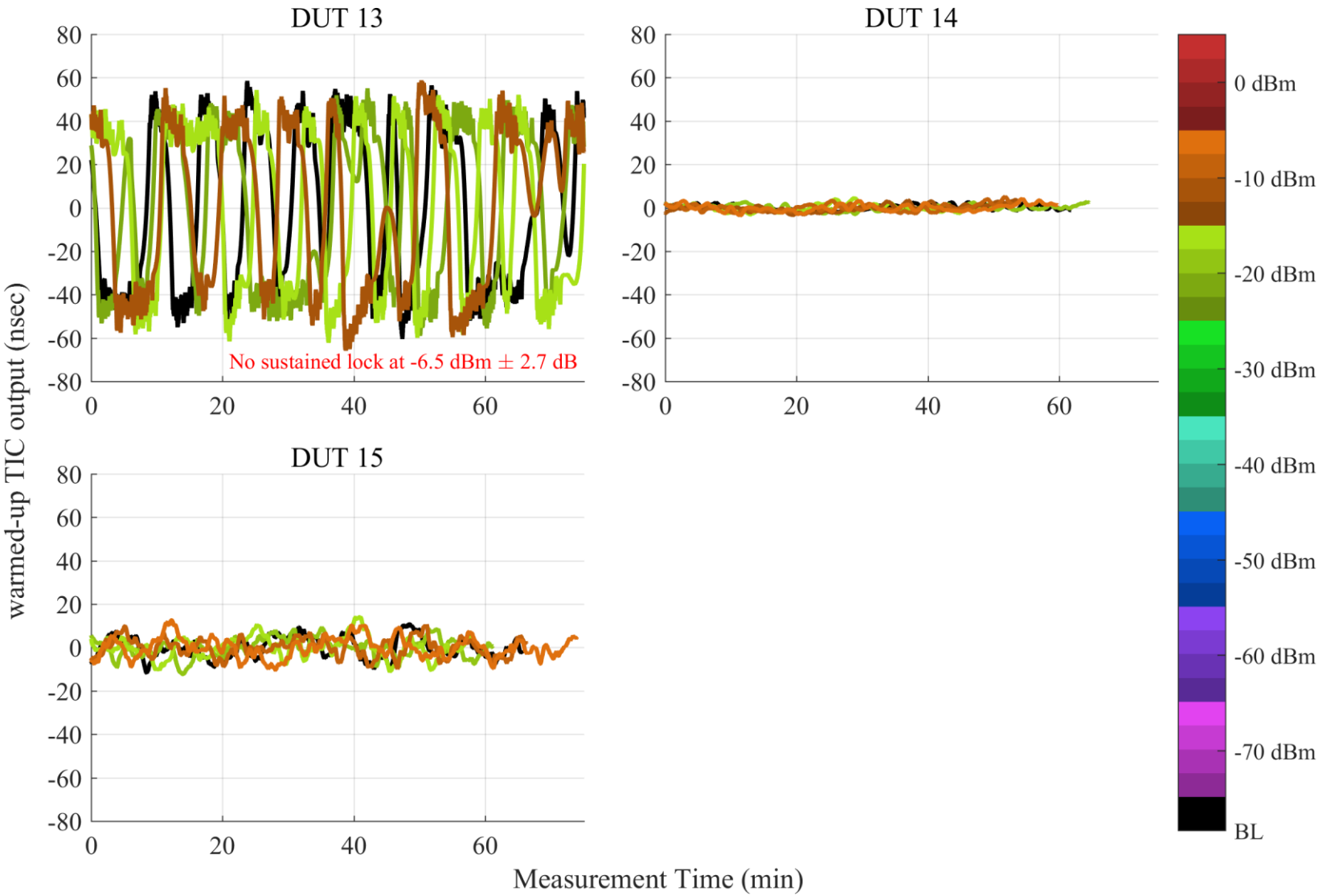

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Fig. 6.76 – pg. 198

Timing

- Allan Time Deviation Estimate from ΔT after Warm-up time
- Uplink 1
- Nominal satellite condition

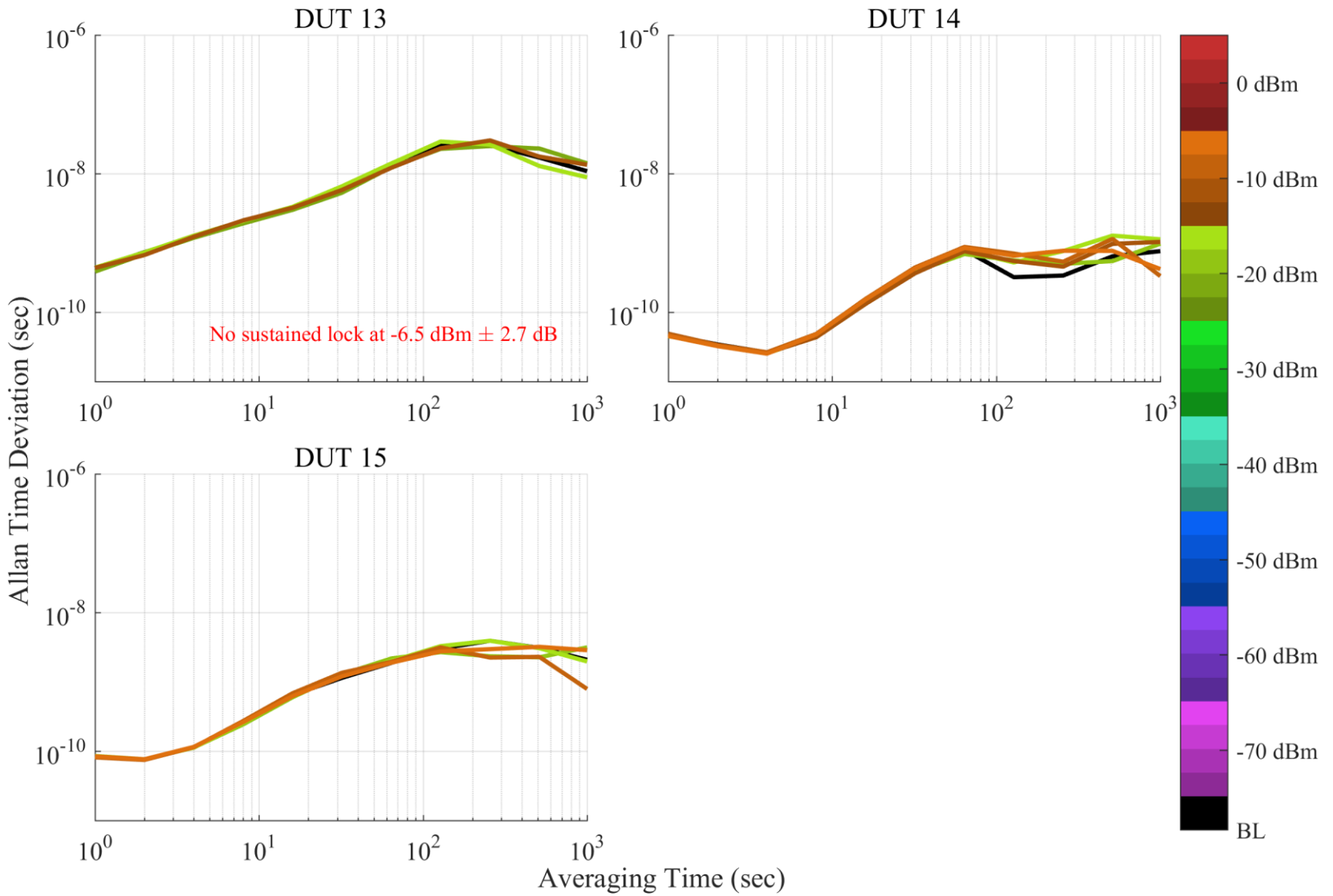

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Fig. 6.77 – pg. 199

Zoomed TDEV

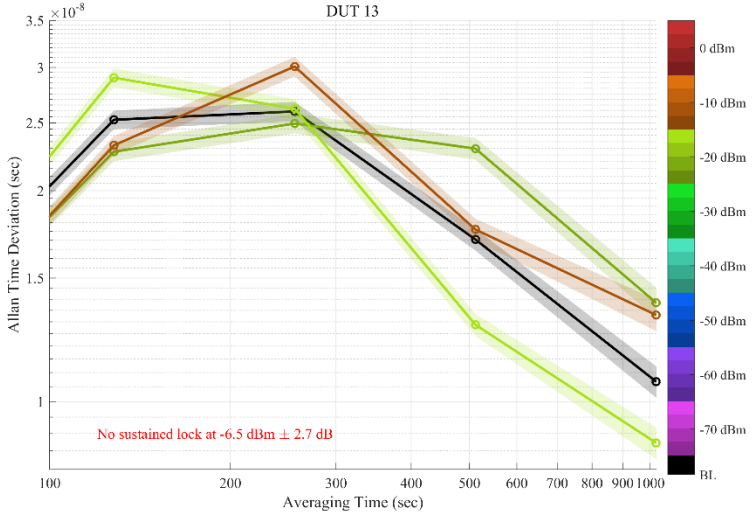

Fig. 6.78 – pg. 200

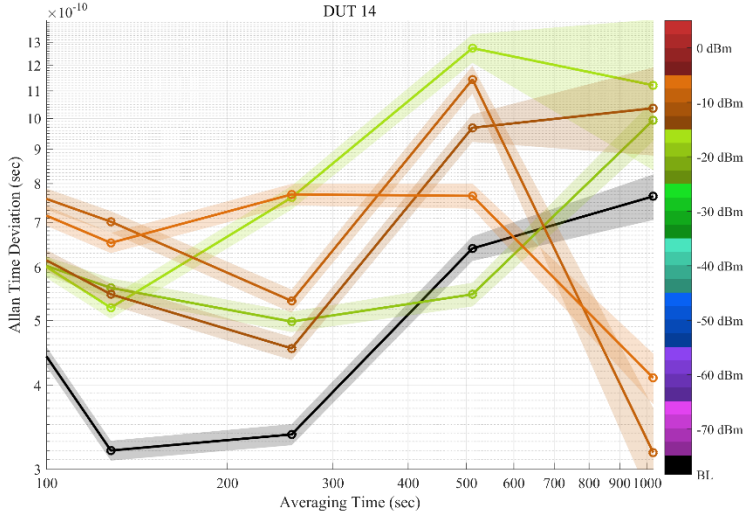

Fig. 6.79 – pg. 201

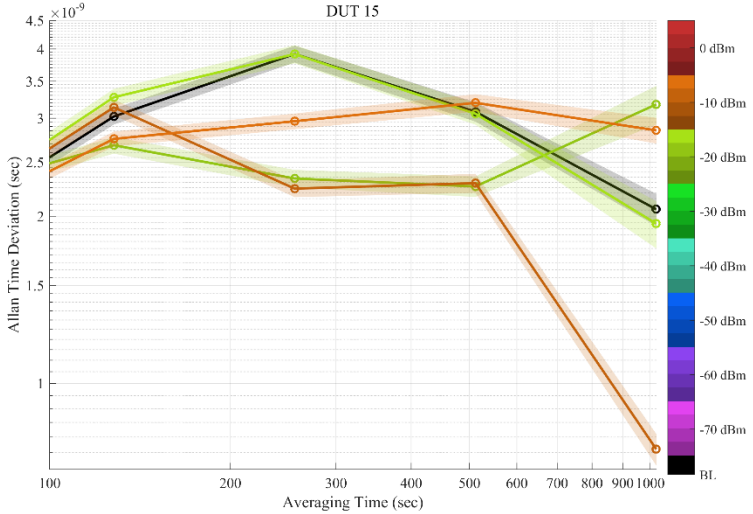

Fig. 6.80 – pg. 202

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Timing

- Number of reported satellites in view scatter plot
- Uplink 1
- Nominal satellite condition

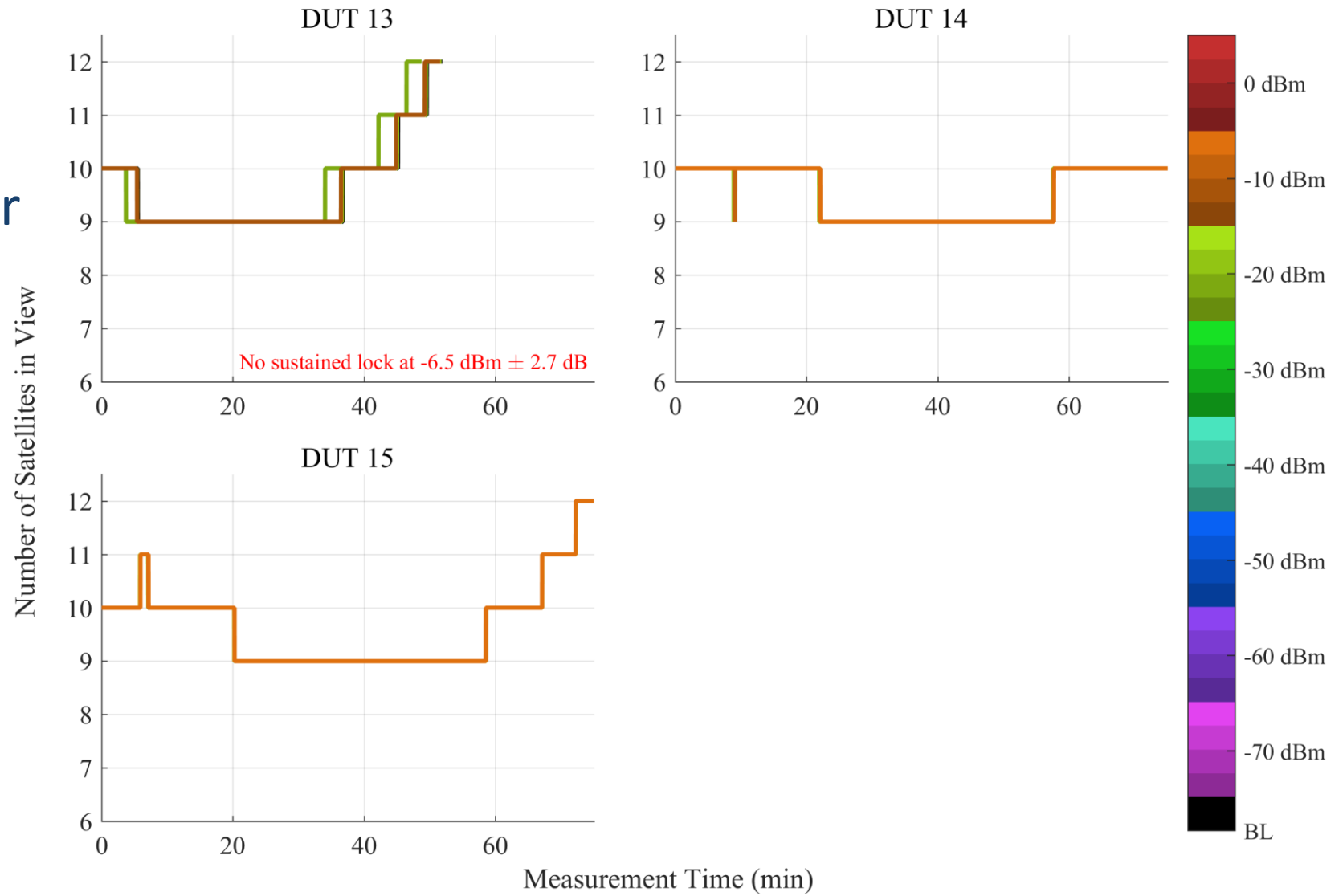

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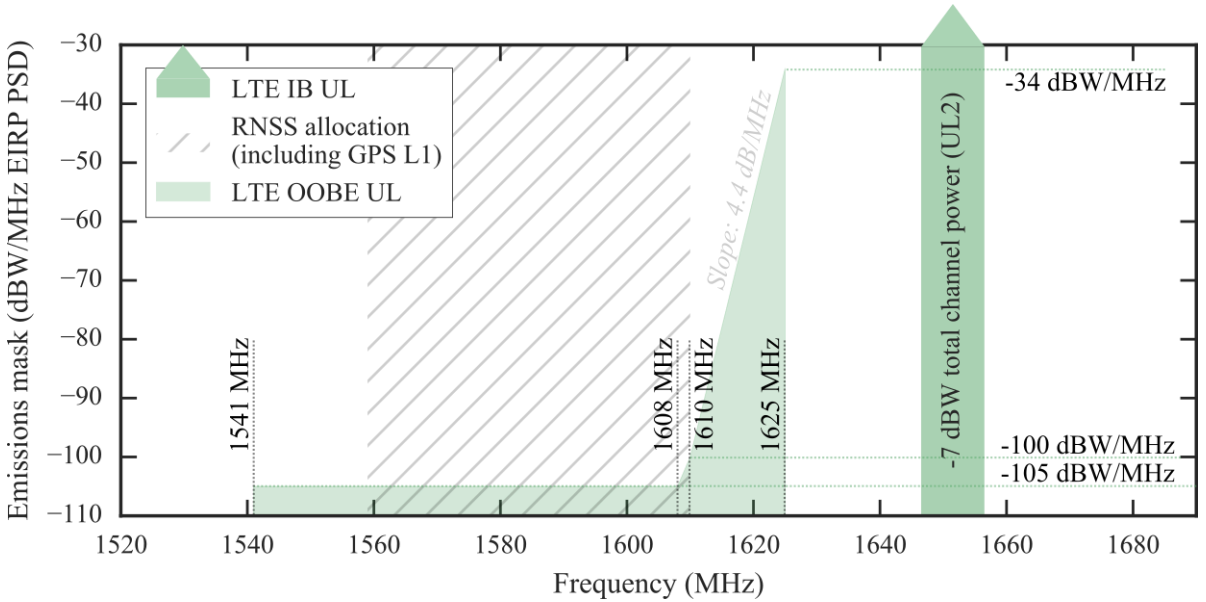
Fig. 6.82 – pg. 204

Timing

- Nominal Satellite Condition
- Timing
  - Downlink
  - Uplink 1
  - **Uplink 2**
  - Combo DL + UL1



Timing

- C/N0 scatter plots (top)
- 95% confidence regions for median C/N_0 (bottom)
- Uplink 2
- Nominal satellite condition

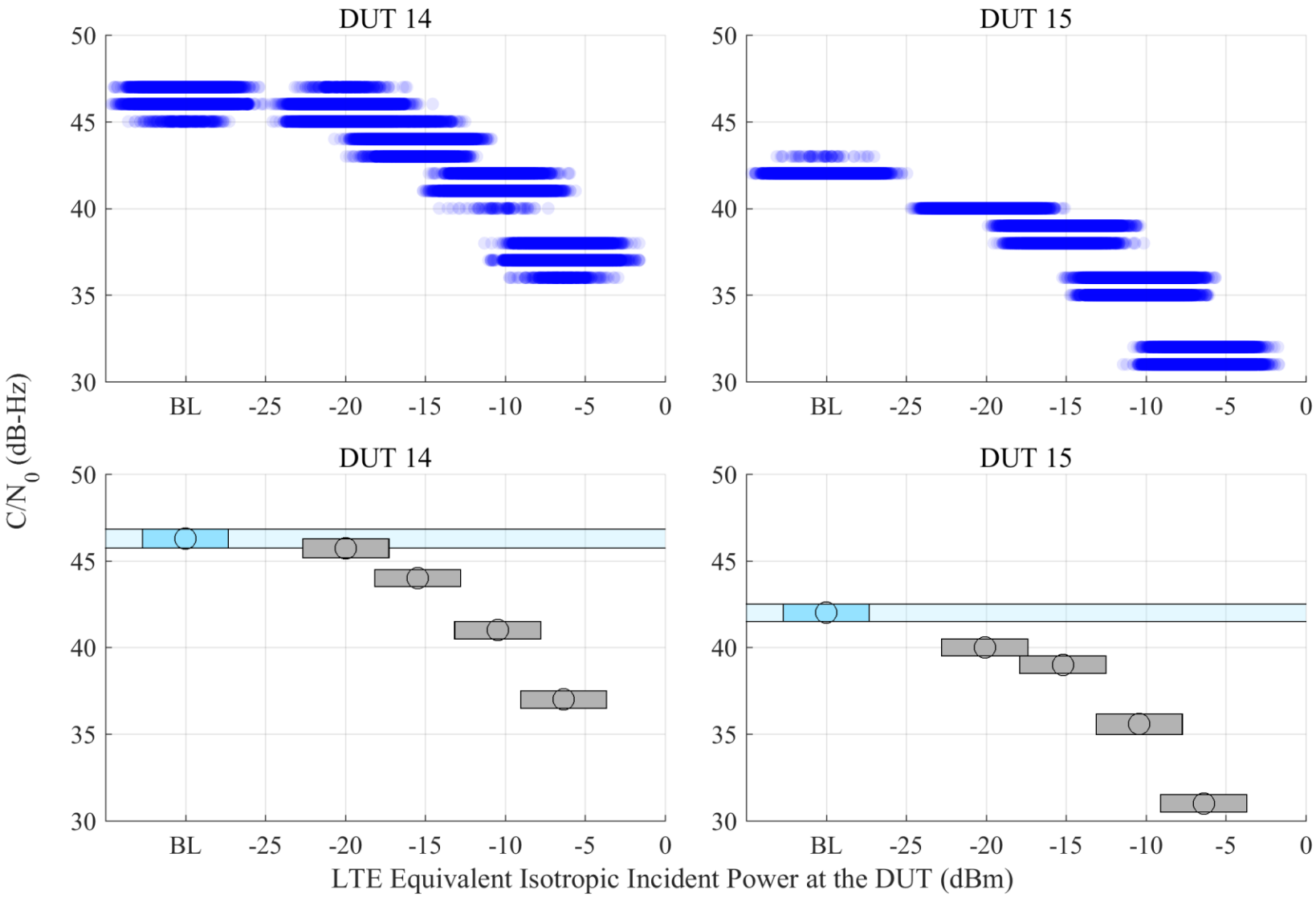


Fig. 6.88 – pg. 210

Timing

- $\Delta T = PPS_{CSClock} - PPS_{DUT}$
- TIC data after Warm-up estimation
- Uplink 2
- Nominal satellite condition

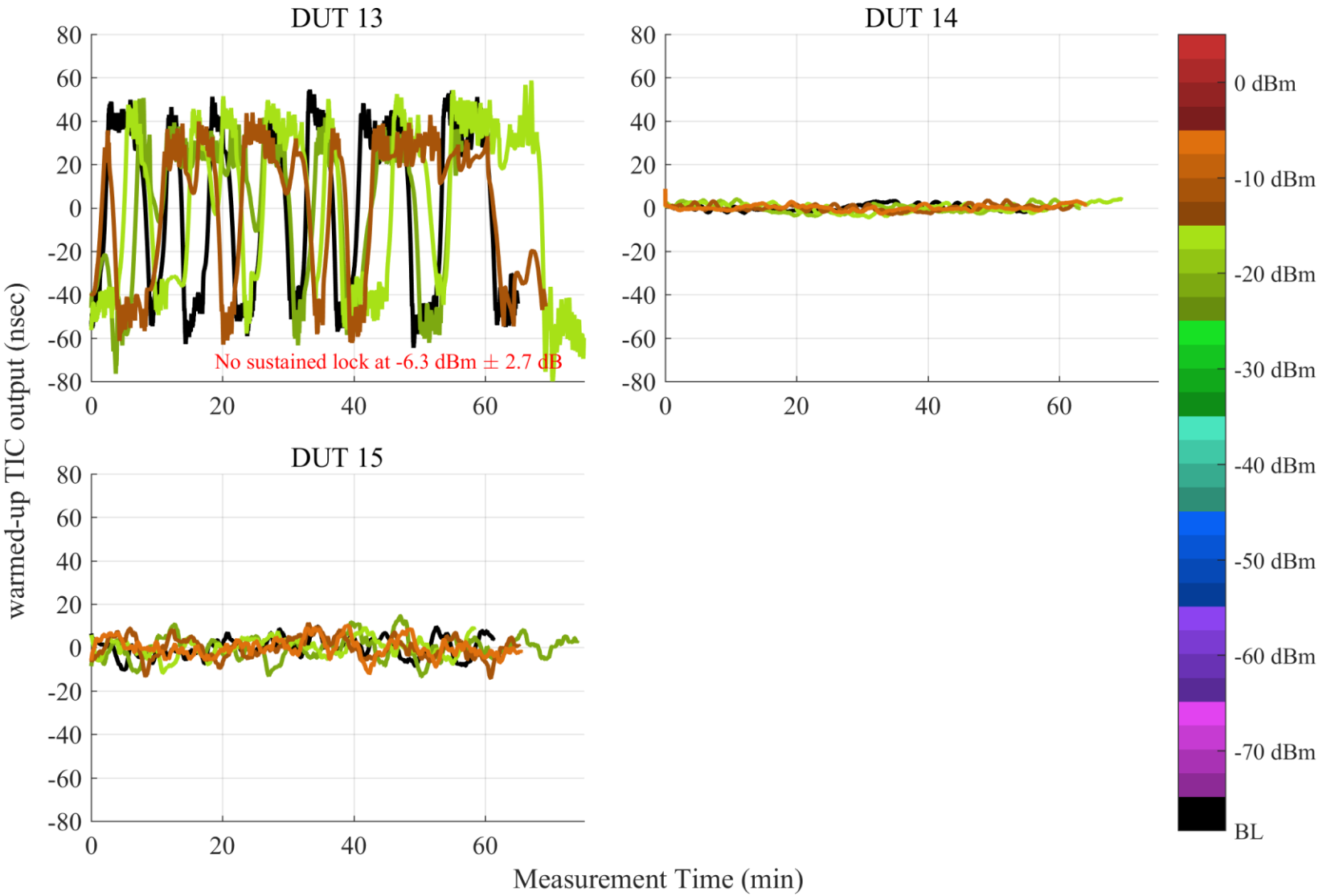


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Fig. 6.83 – pg. 205

Timing

- Allan Time Deviation Estimate from ΔT after Warm-up time
- Uplink 2
- Nominal satellite condition

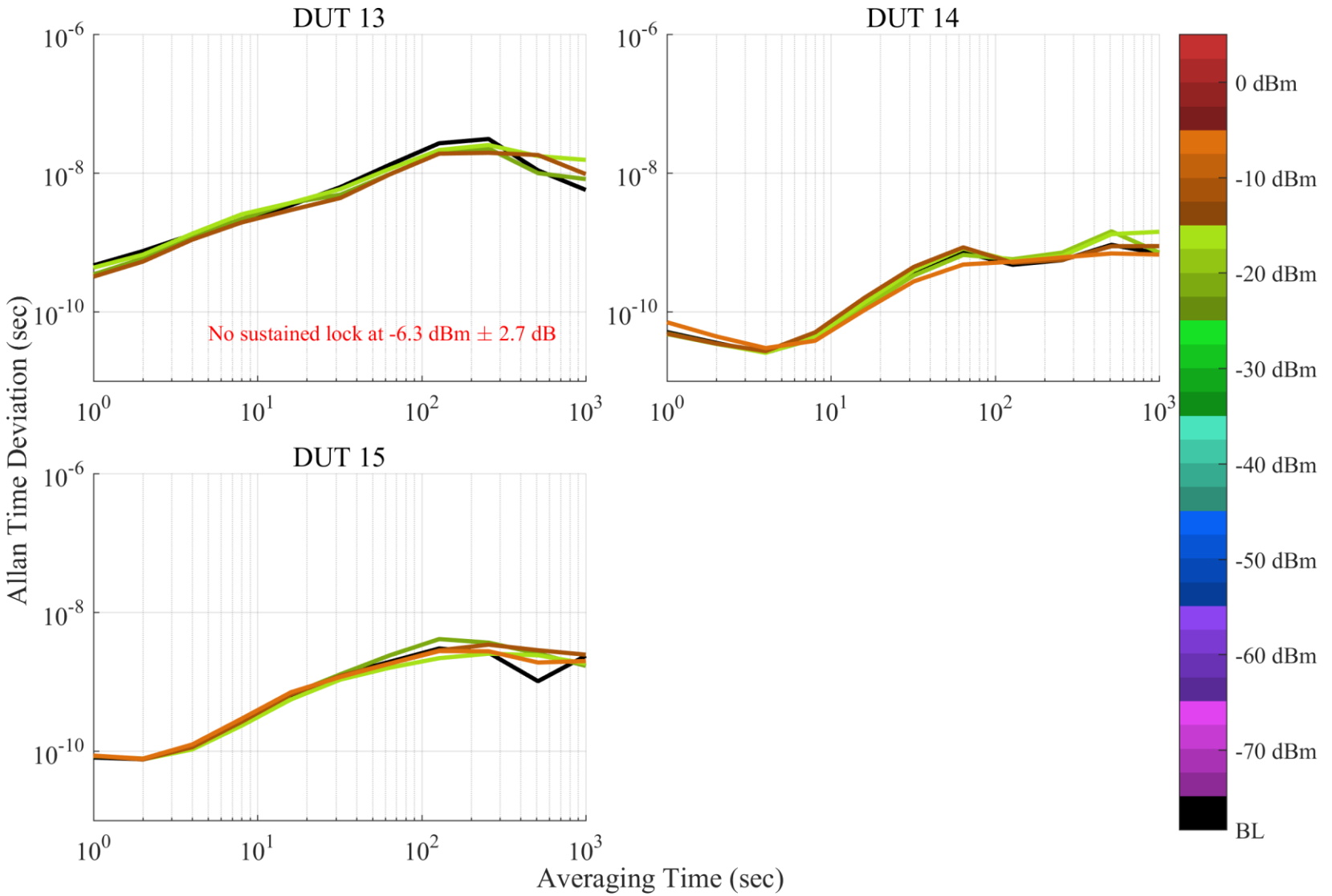

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Fig. 6.84 – pg. 206

Zoomed TDEV

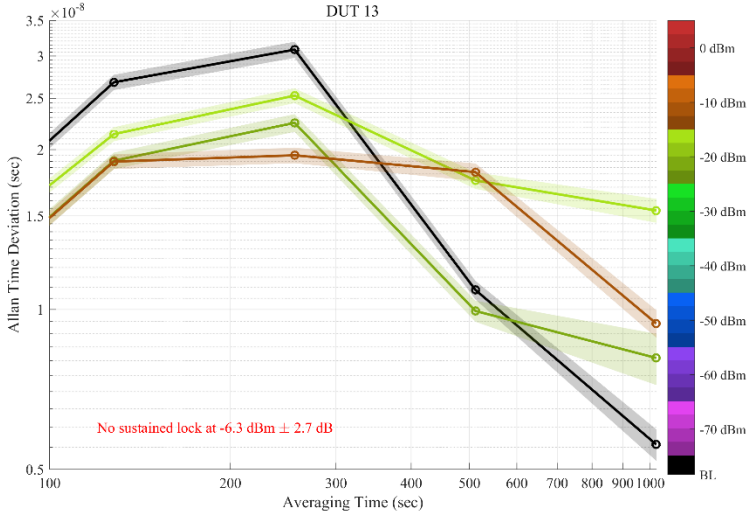

Fig. 6.85 – pg. 207

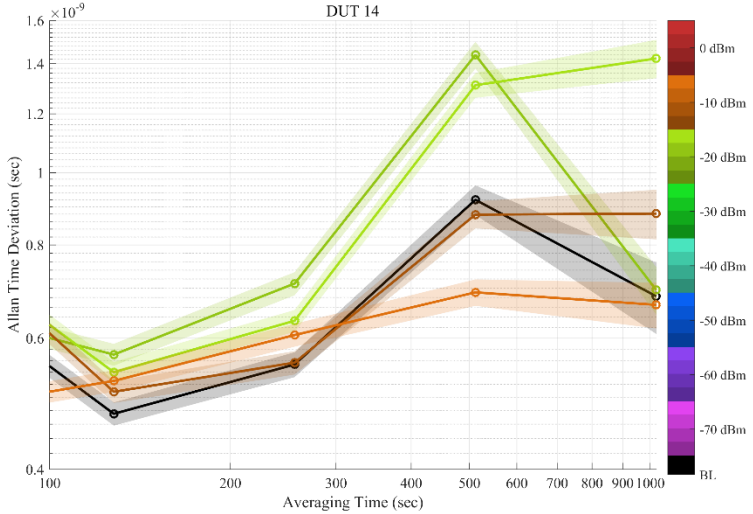

Fig. 6.86 – pg. 208

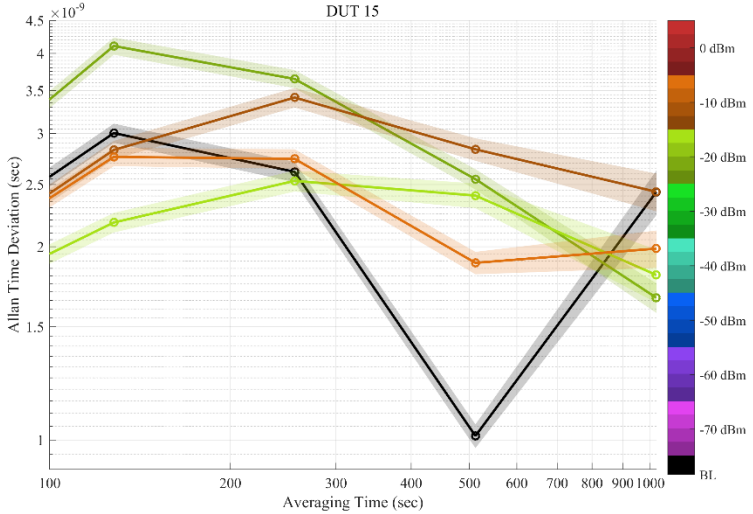

Fig. 6.87 – pg. 209

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Timing

- Number of reported satellites in view scatter plot
- Uplink 2
- Nominal satellite condition

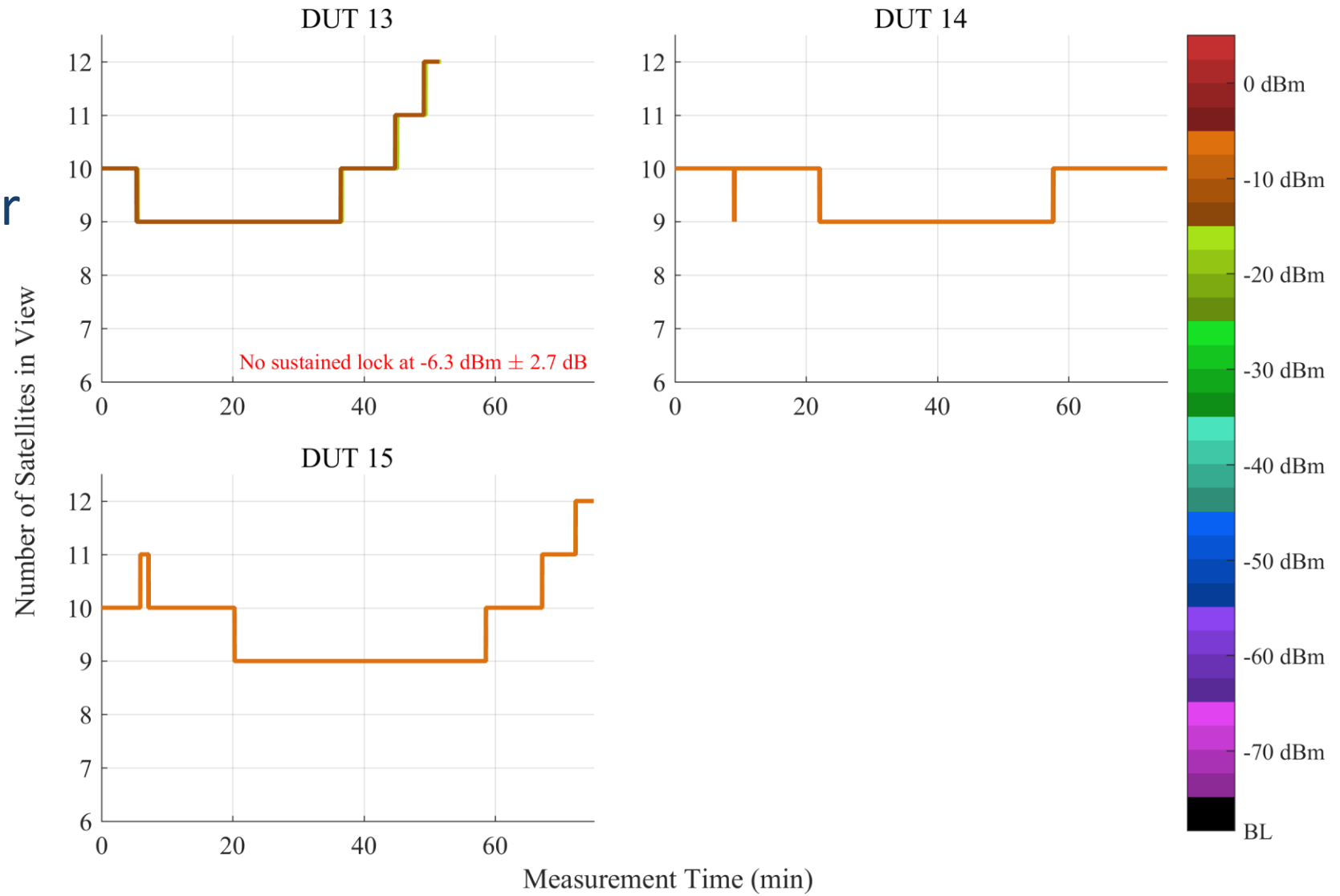

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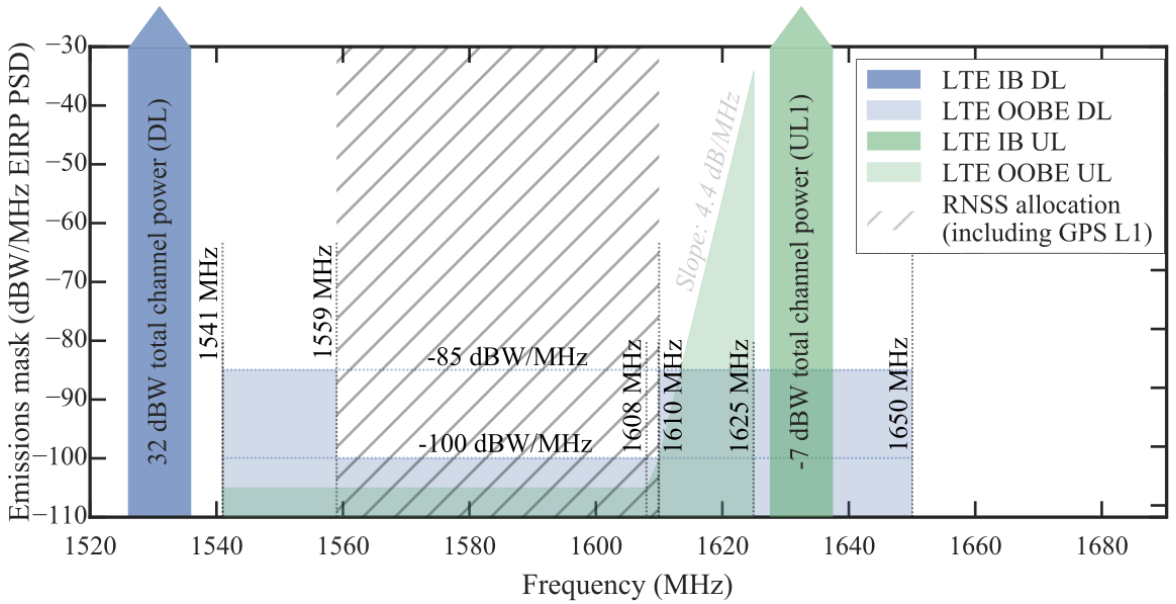
Fig. 6.89 – pg. 211

Timing

- Nominal Satellite Condition
- Timing
  - Downlink
  - Uplink 1
  - Uplink 2
  - **Combo DL + UL1**



Timing

- C/N0 scatter plots (top)
- 95% confidence regions for median C/N_0 (bottom)
- Combo DL +UL1
- Nominal satellite condition
- DL fixed: -50 dBm

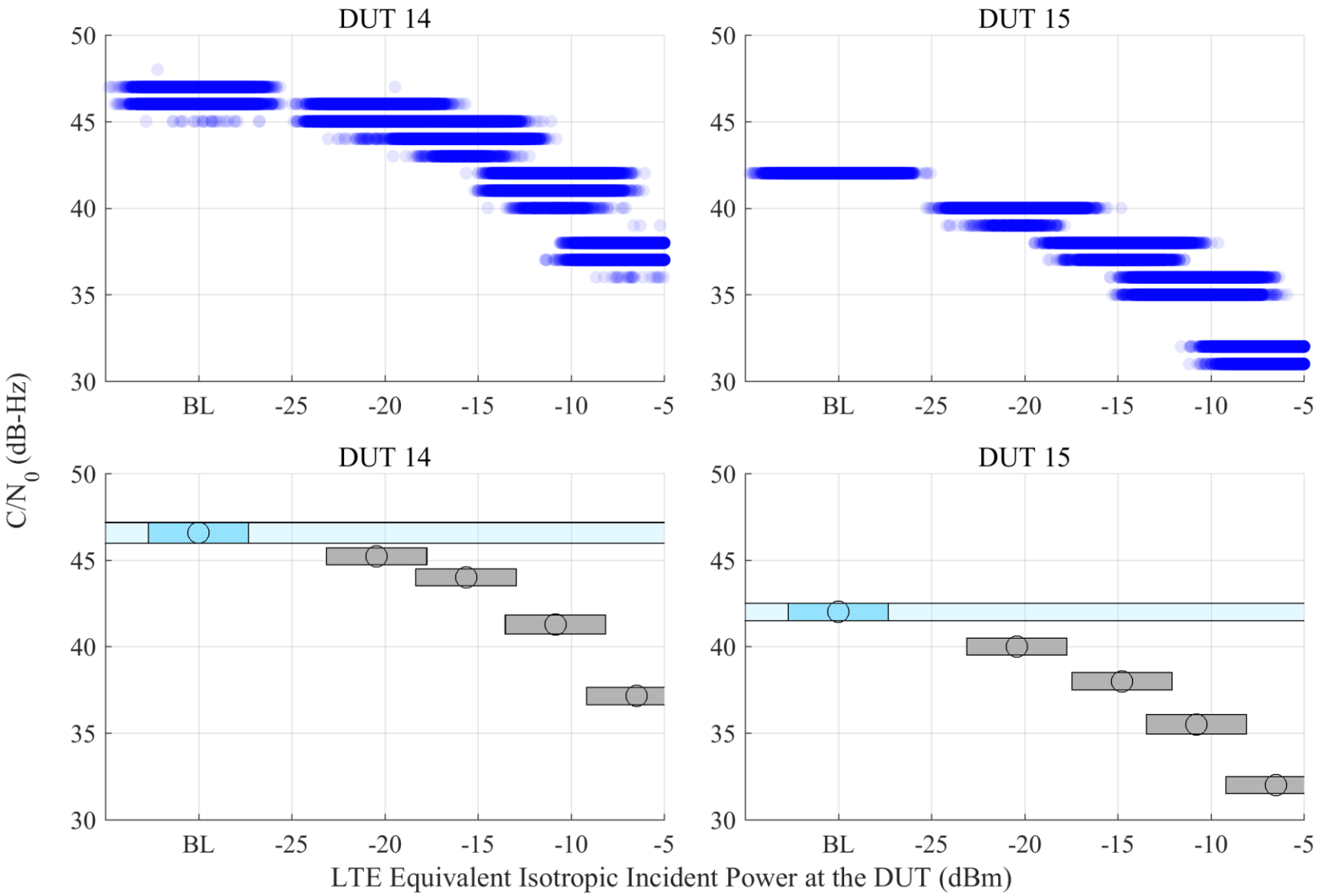


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Fig. 6.95 – pg. 217

Timing

- $\Delta T = PPS_{CSClock} - PPS_{DUT}$
- TIC data after Warm-up estimation
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm

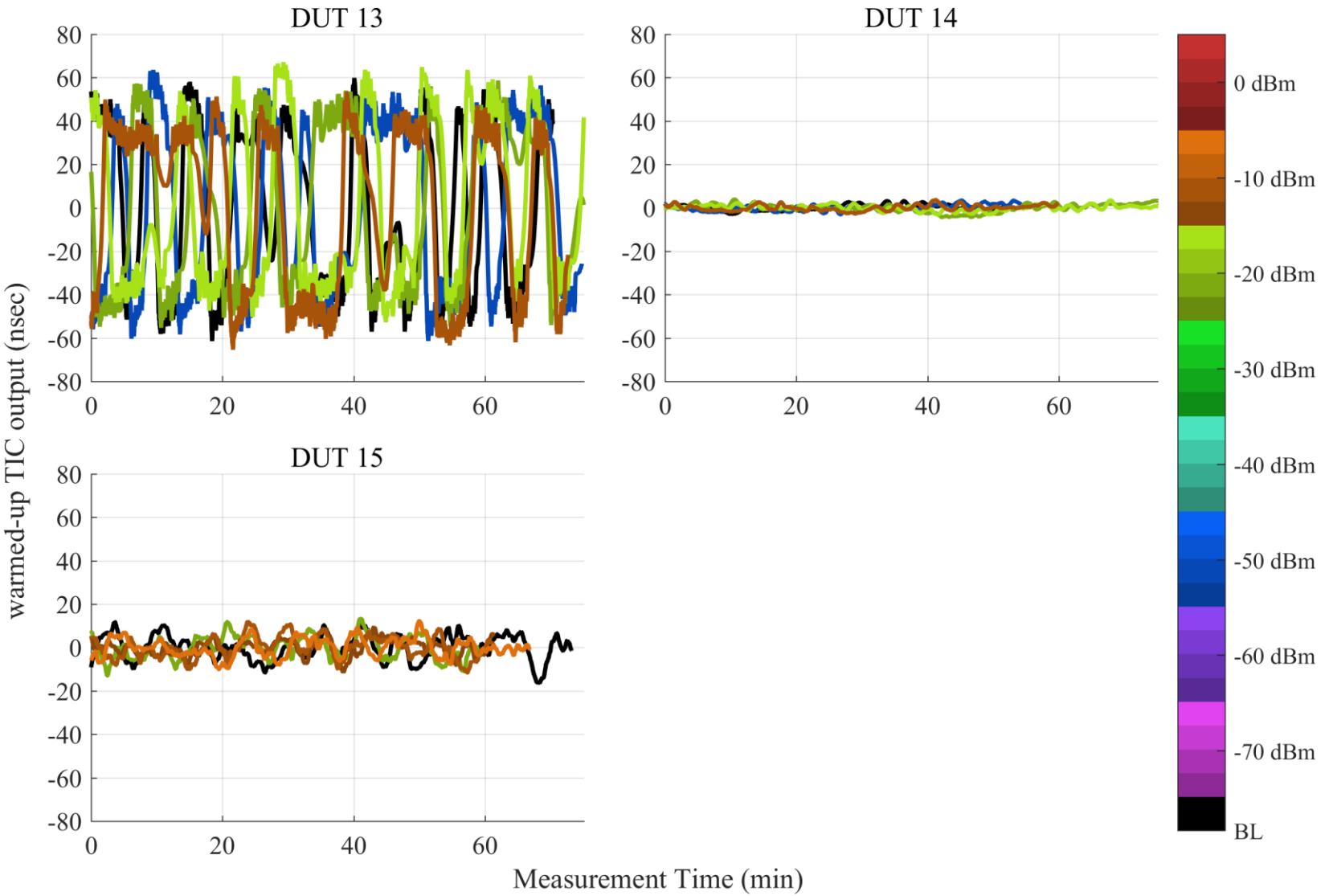

Fig. 6.90 – pg. 212

Timing

- Allan Time Deviation Estimate from ΔT after Warm-up time
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm

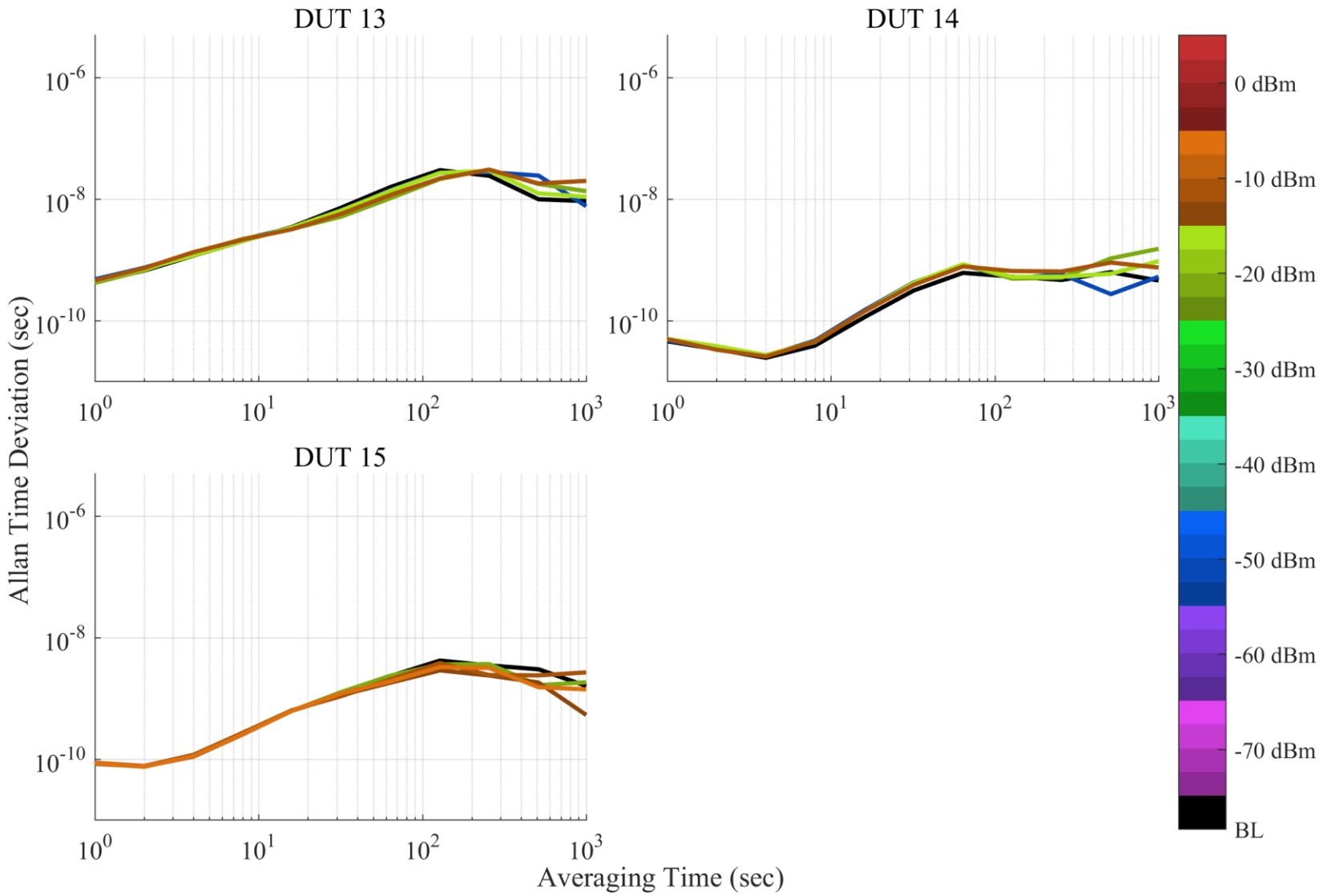

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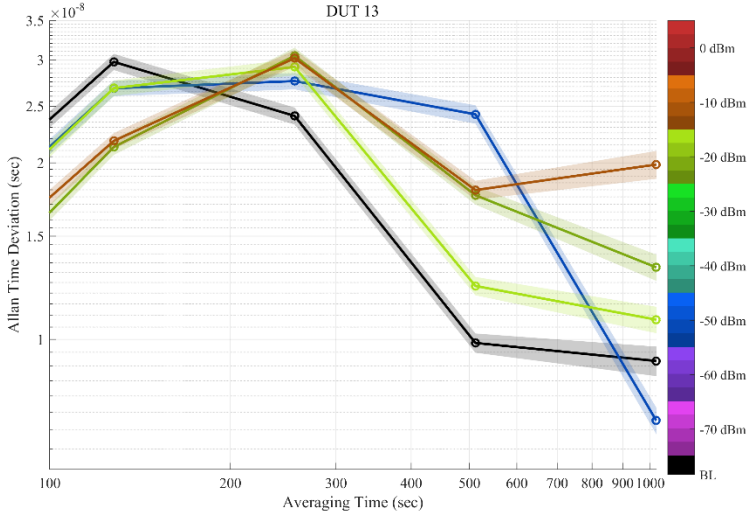
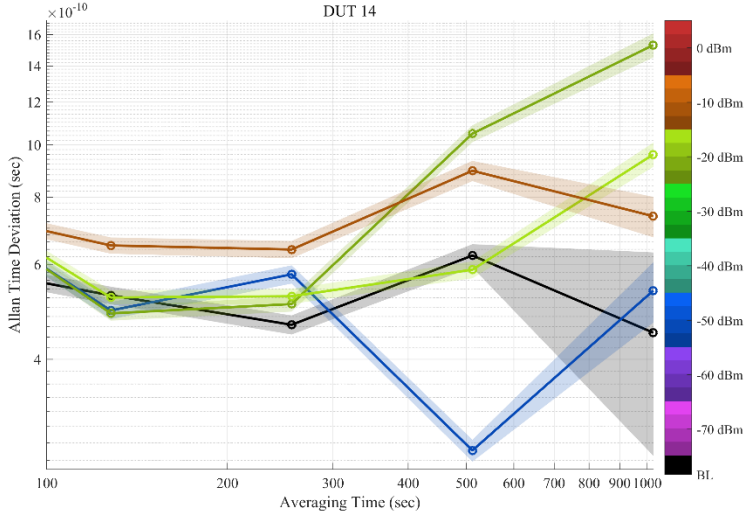
Fig. 6.91 – pg. 213

Zoomed TDEV





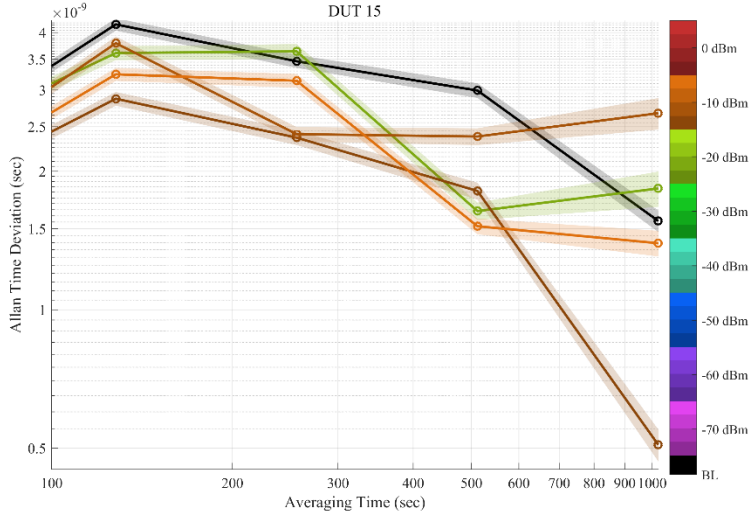


Fig. 6.92 – pg. 214

Fig. 6.93 – pg. 215

Fig. 6.94 – pg. 216

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Timing

- Number of reported satellites in view scatter plot
- Combo DL + UL1
- Nominal satellite condition
- DL fixed: -50 dBm

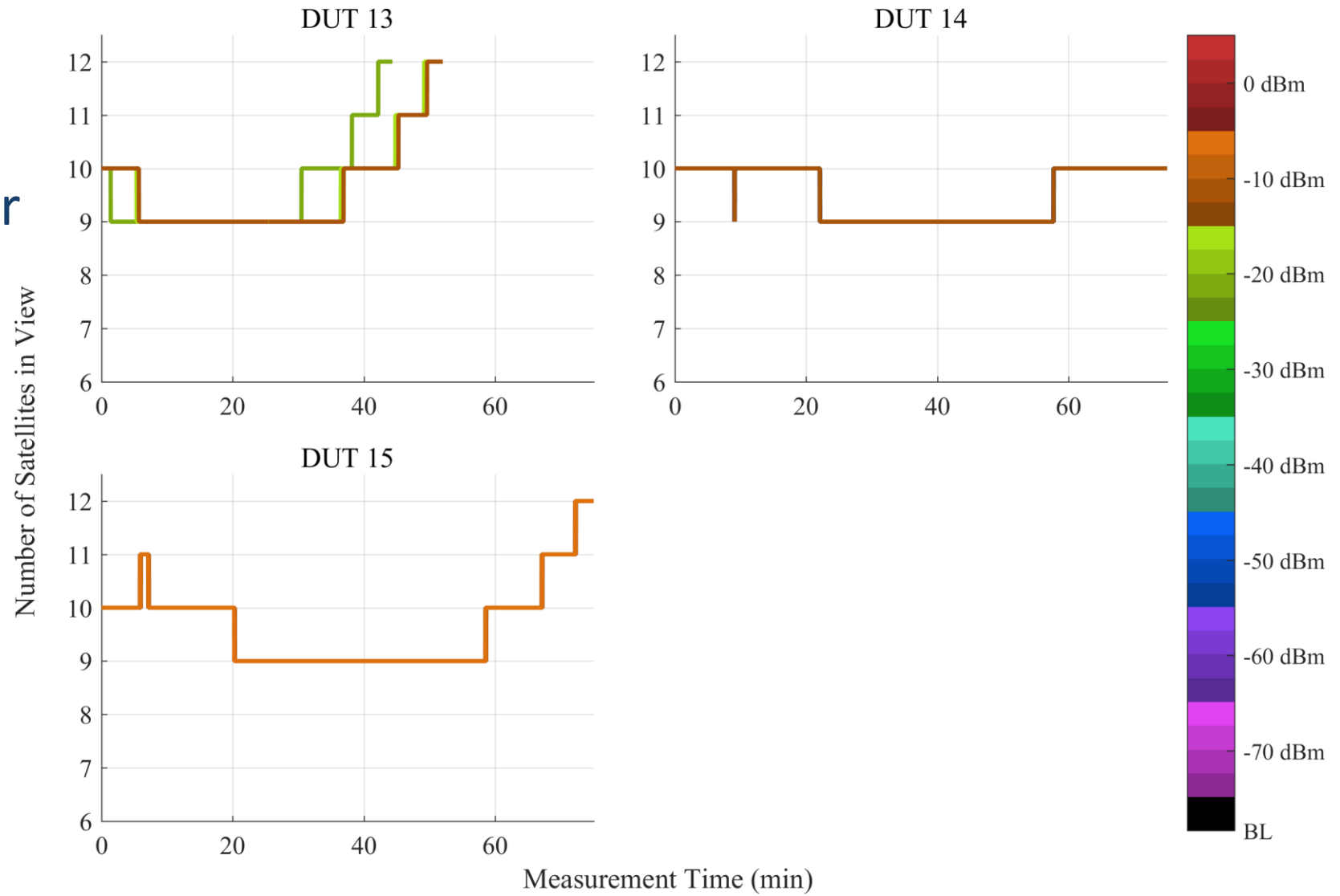

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Fig. 6.96 – pg. 218

Development Board GPS Receivers

Nominal Satellite Constellation

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DEV Antenna Response

- External DUT antenna was measured
- Active antenna response is normalized

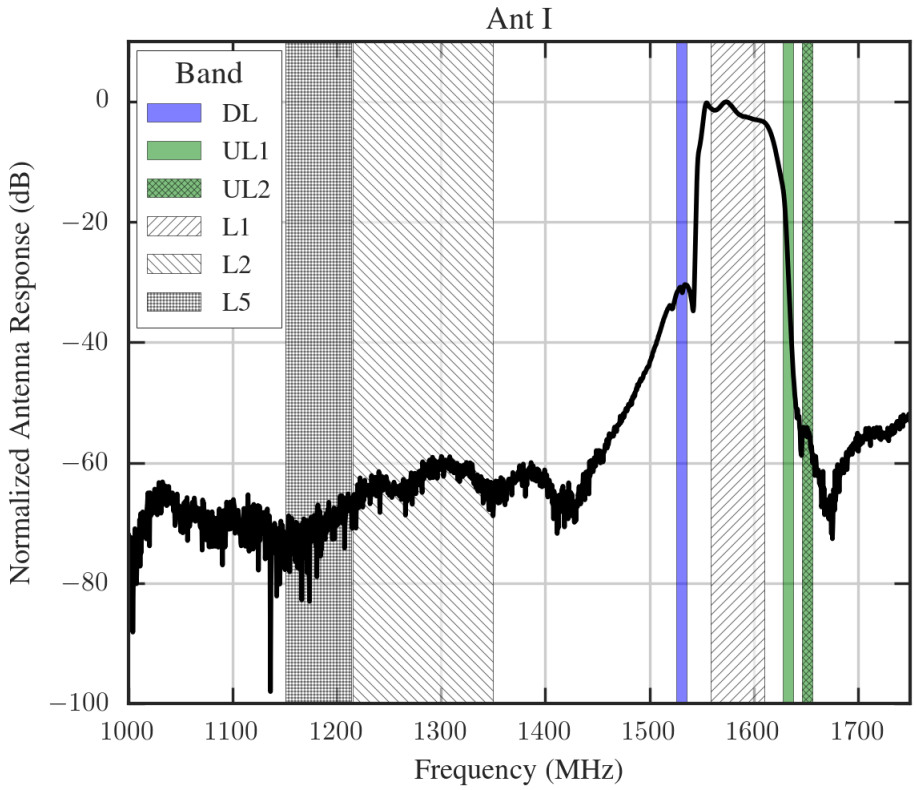

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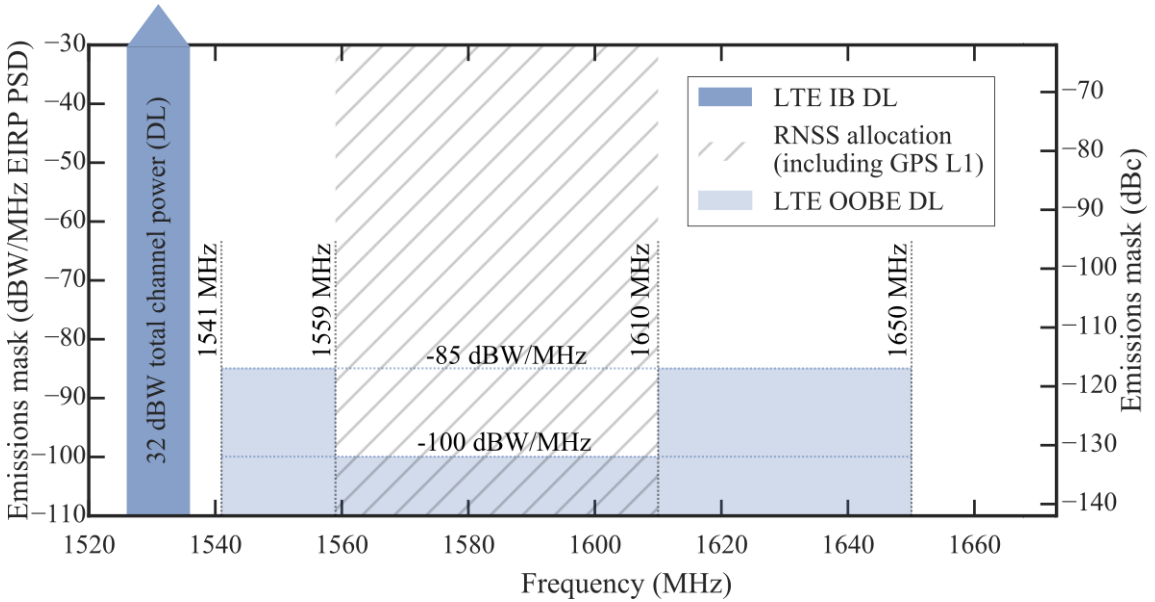
Fig. F.2 – pg. 351

Development Board GPS Receivers

- Nominal Satellite Condition
  - **Downlink**
  - Uplink 1
  - Uplink 2
  - Combo DL + UL1



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DEV Board

- C/N0 plots
- Downlink
- Nominal satellite condition
- 1200 points per LTE power level per satellite

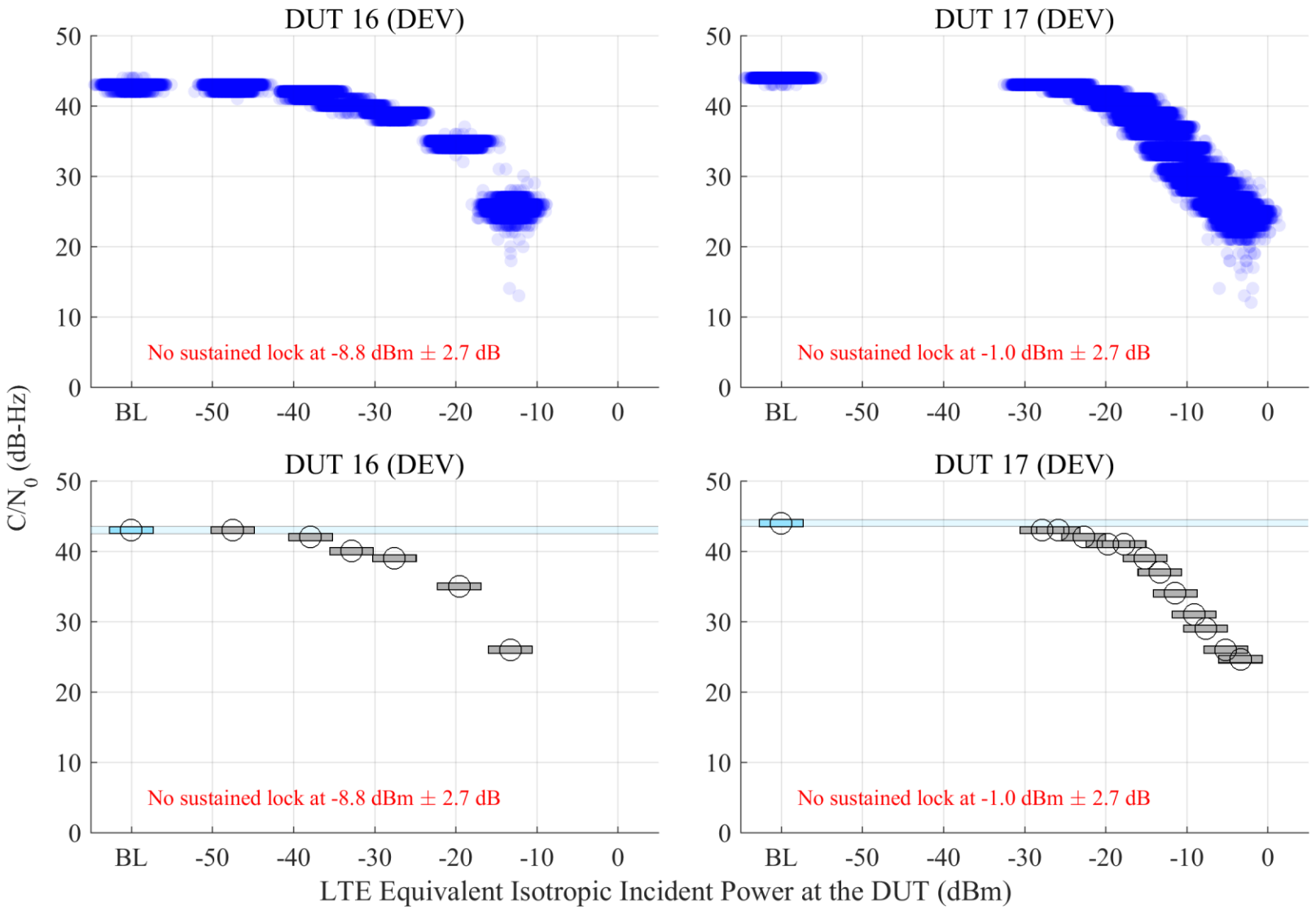

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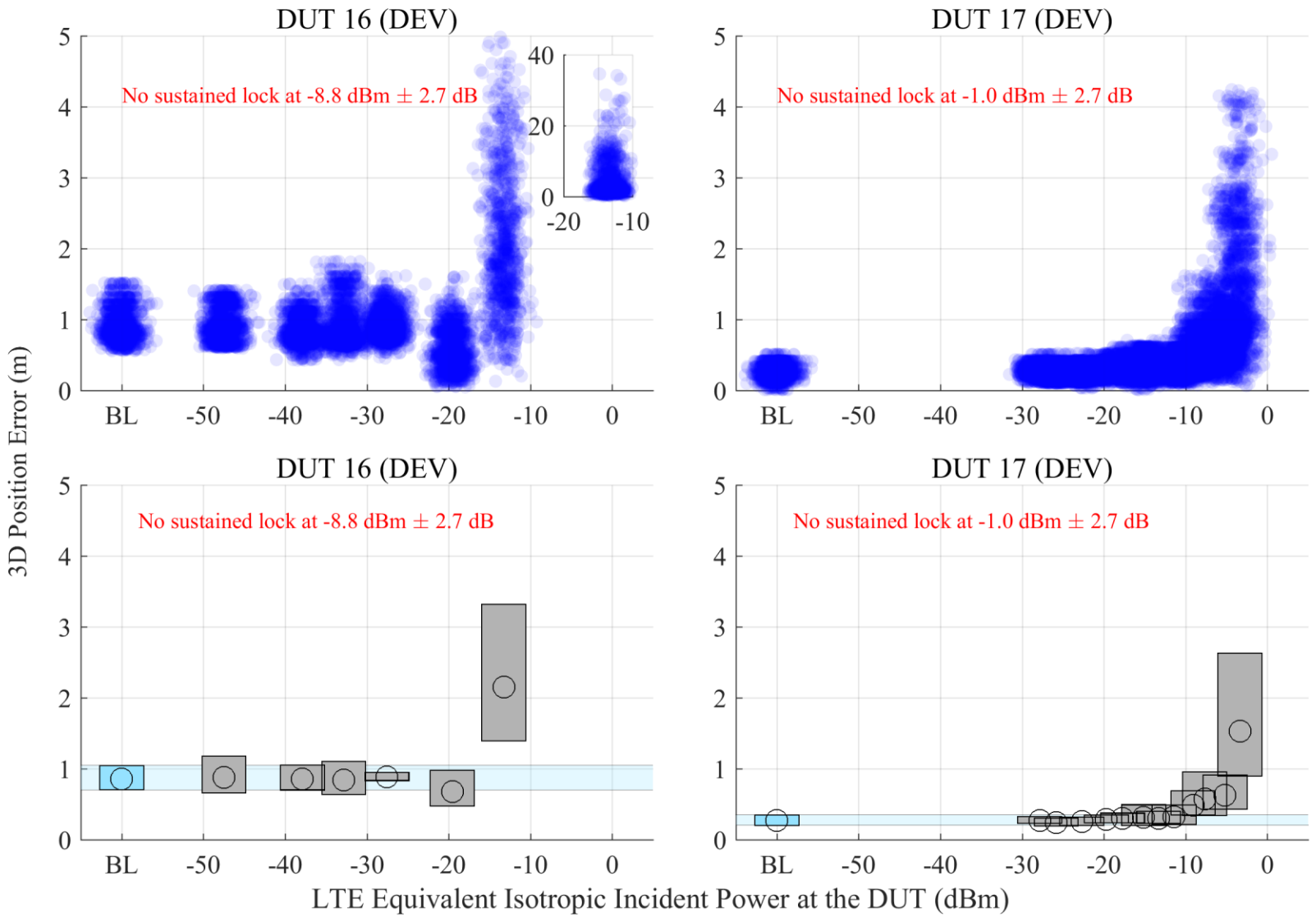
Fig. F.3 – pg. 353

DEV Board

- 3D position error
- Downlink
- Nominal satellite condition

Baseline (BL) – No LTE Power



NASCTN
National Advanced Spectrum and Communications Test Network

Fig. F.4 – pg. 354

DEV Board

- Number of reported satellites in view scatter plot
- Downlink
- Nominal satellite condition

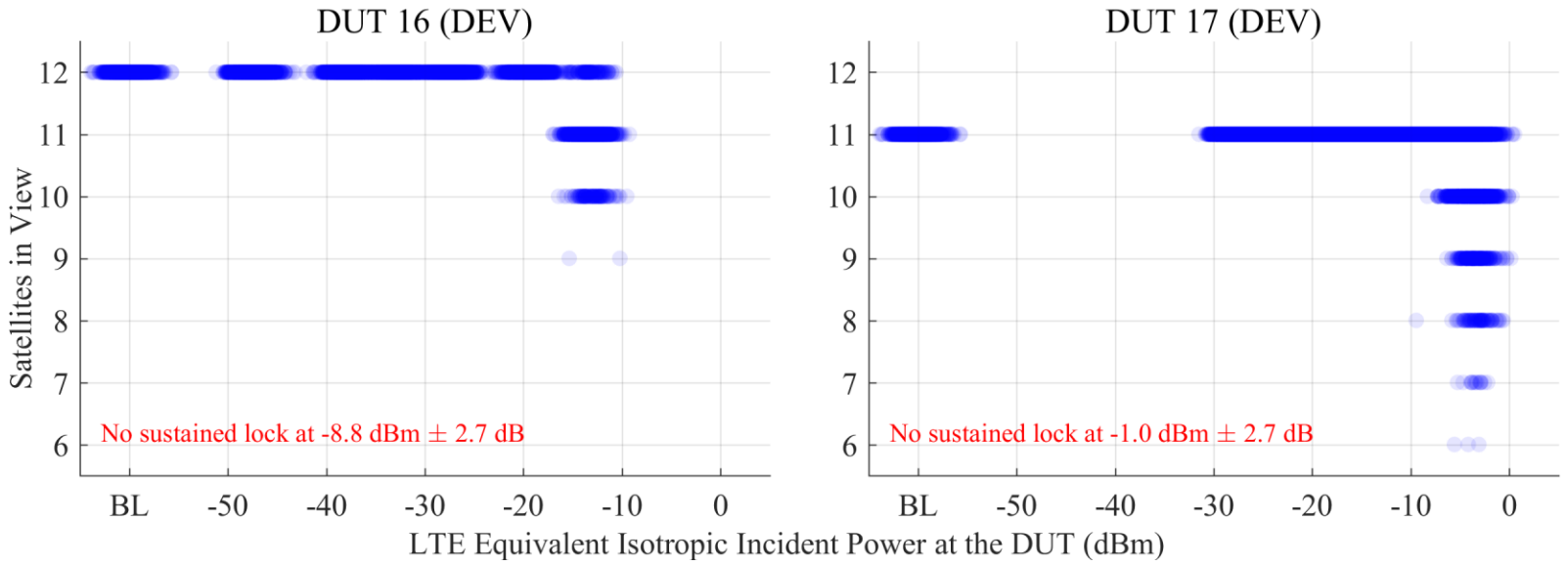
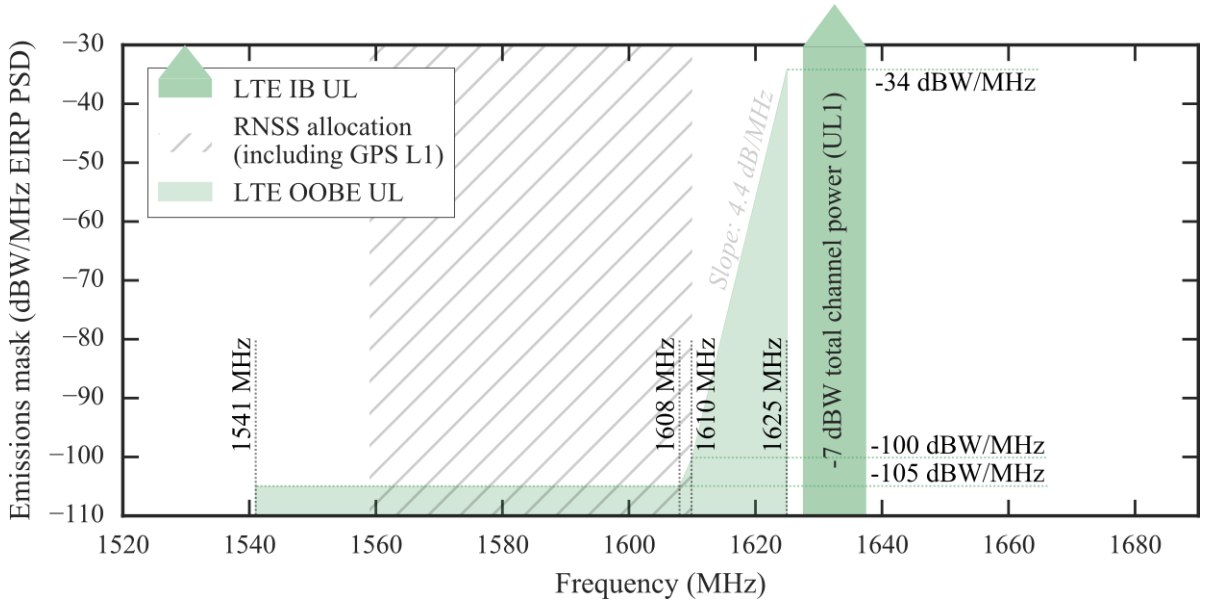


Fig. F.5 – pg. 355

Development Board GPS Receivers

- Nominal Satellite Condition
  - Downlink
  - **Uplink 1**
  - Uplink 2
  - Combo DL + UL1



DEV Board

- C/N0 plots
- Uplink 1
- Nominal satellite condition
- 1200 points per LTE power level per satellite

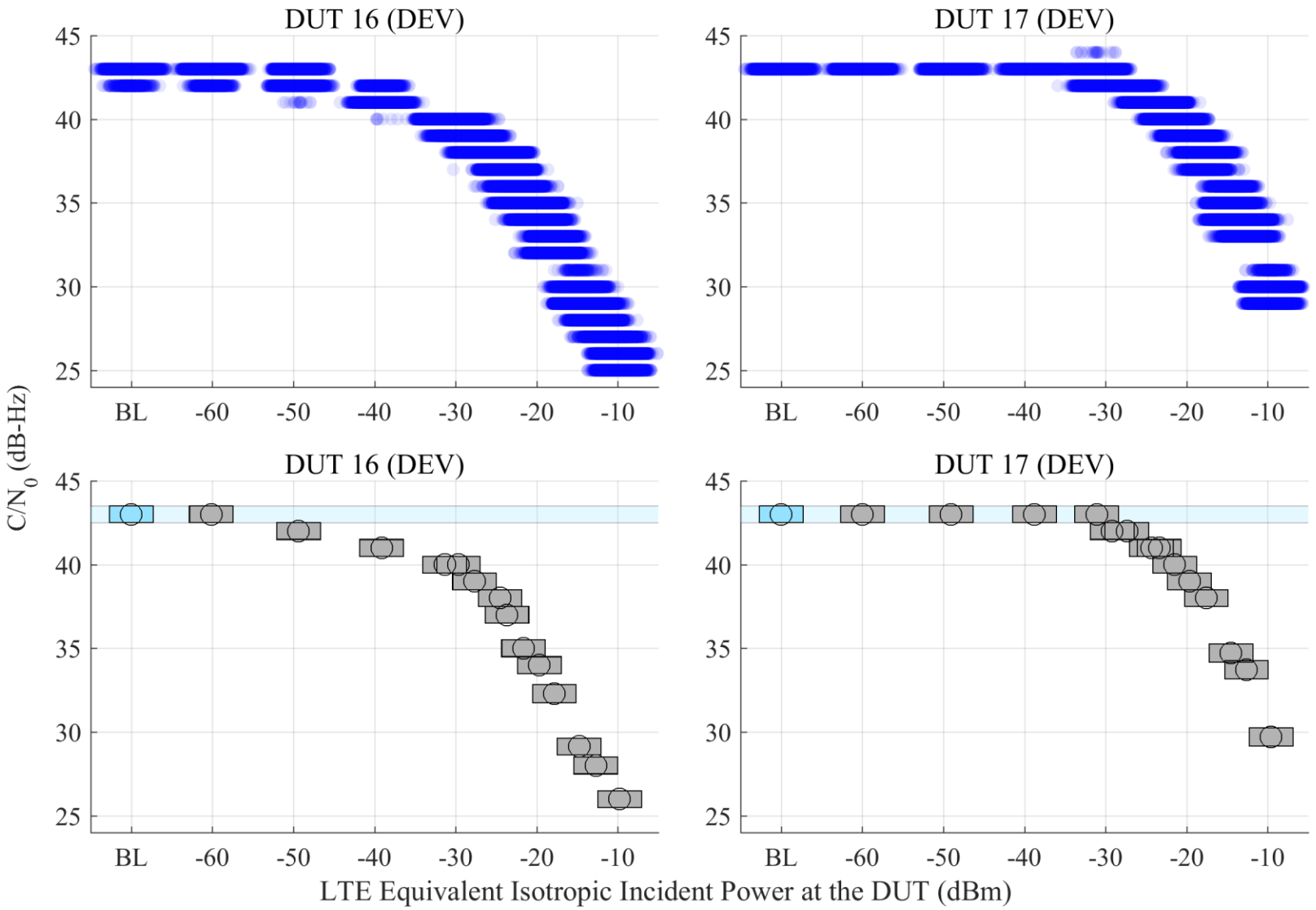


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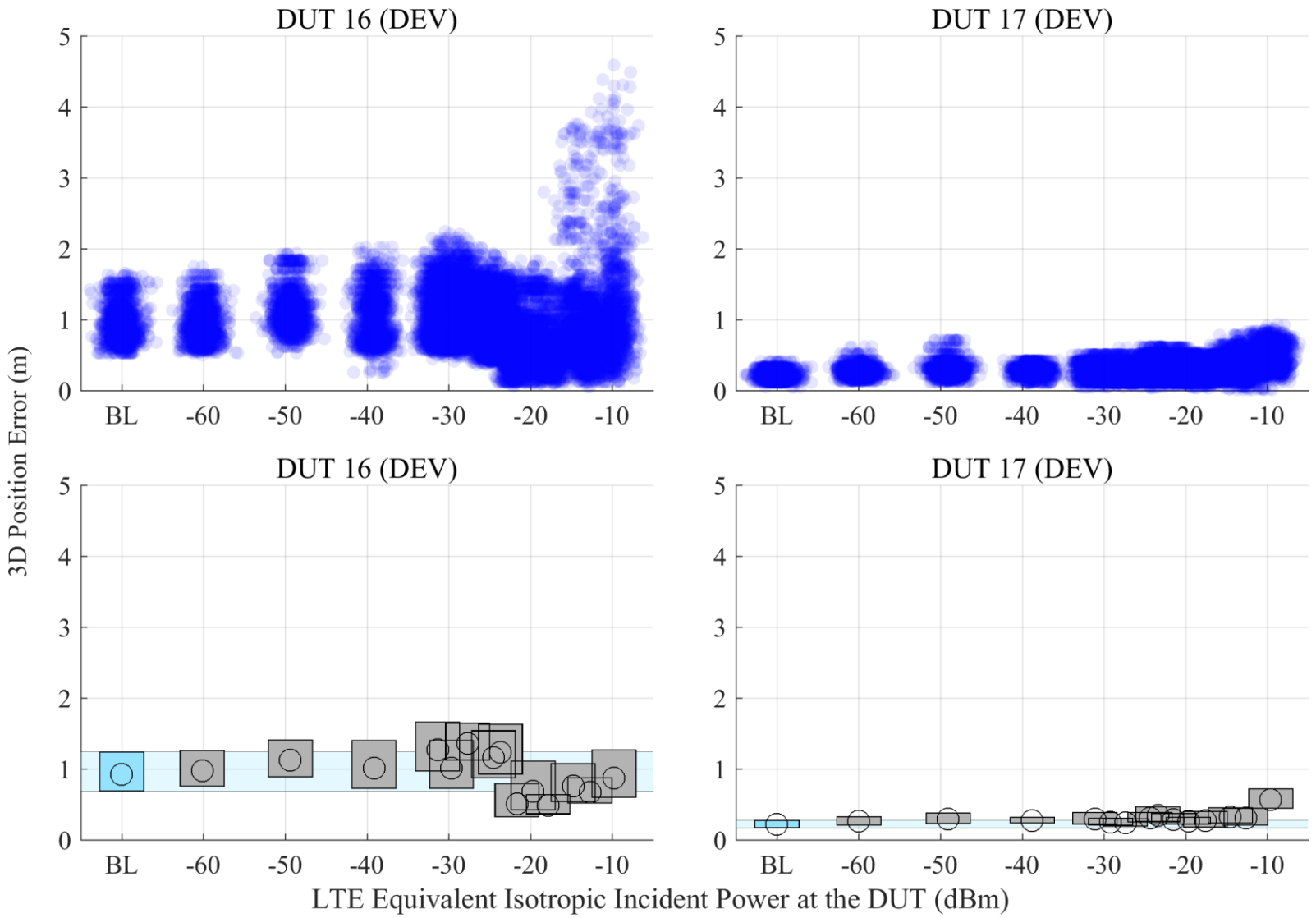
Fig. F.6 – pg. 356

DEV Board

- 3D position error
- Uplink 1
- Nominal satellite condition

Baseline (BL) – No LTE Power



NASCTN
National Advanced Spectrum and Communications Test Network

Fig. F.7 – pg. 357

DEV Board

- Number of reported satellites in view scatter plot
- Uplink 1
- Nominal satellite condition

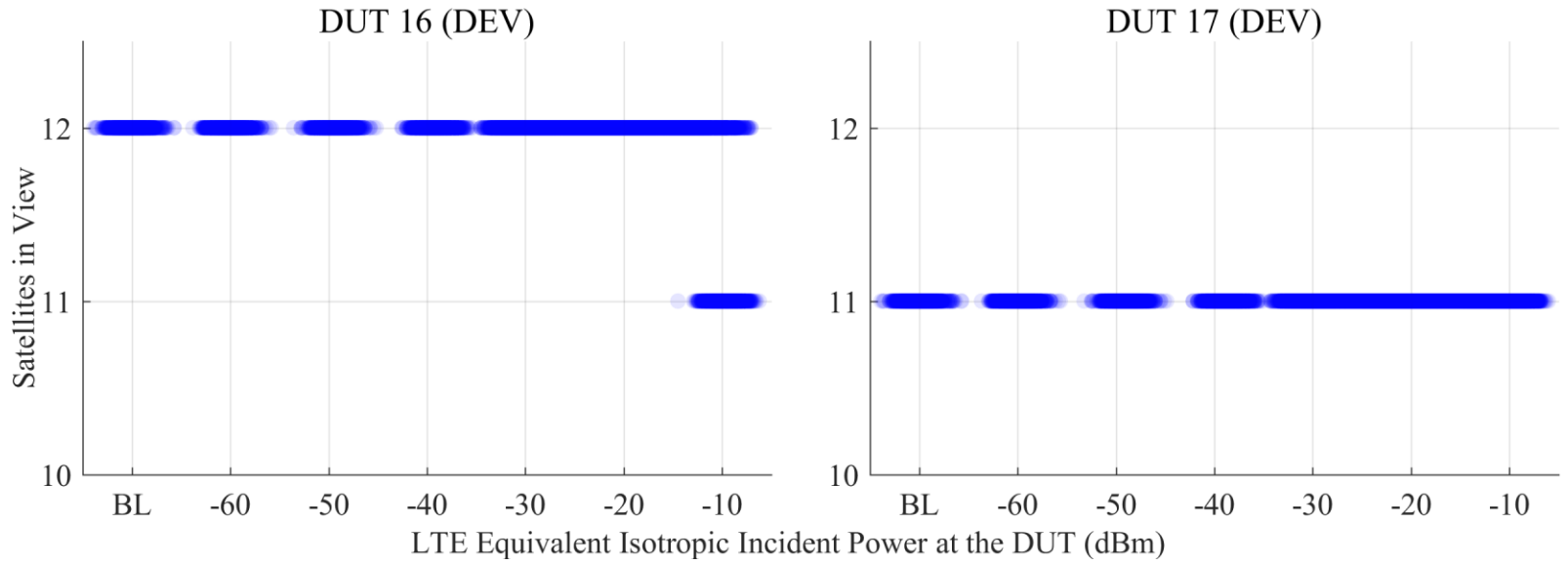


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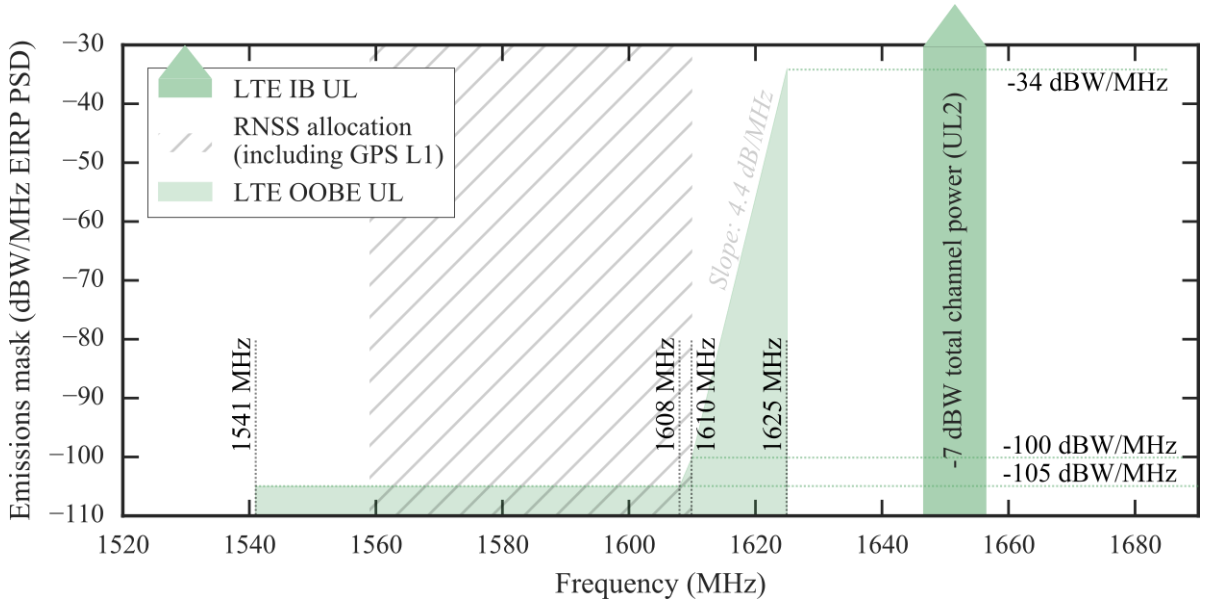
Fig. F.8 – pg. 358

Development Board GPS Receivers

- Nominal Satellite Condition
  - Downlink
  - Uplink 1
  - **Uplink 2**
  - Combo DL + UL1



DEV Board

- C/N0 plots
- Uplink 2
- Nominal satellite condition
- 1200 points per LTE power level per satellite

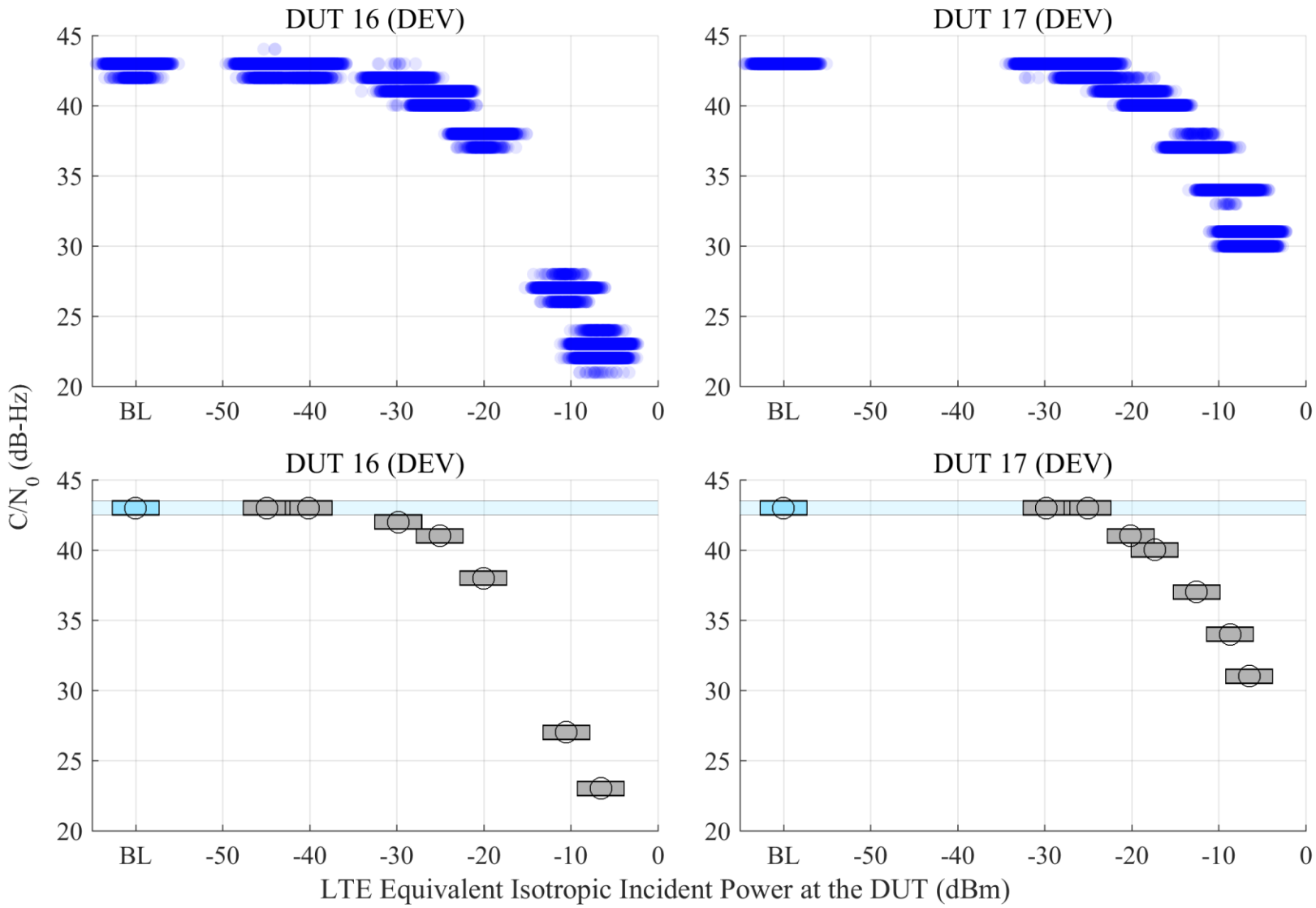


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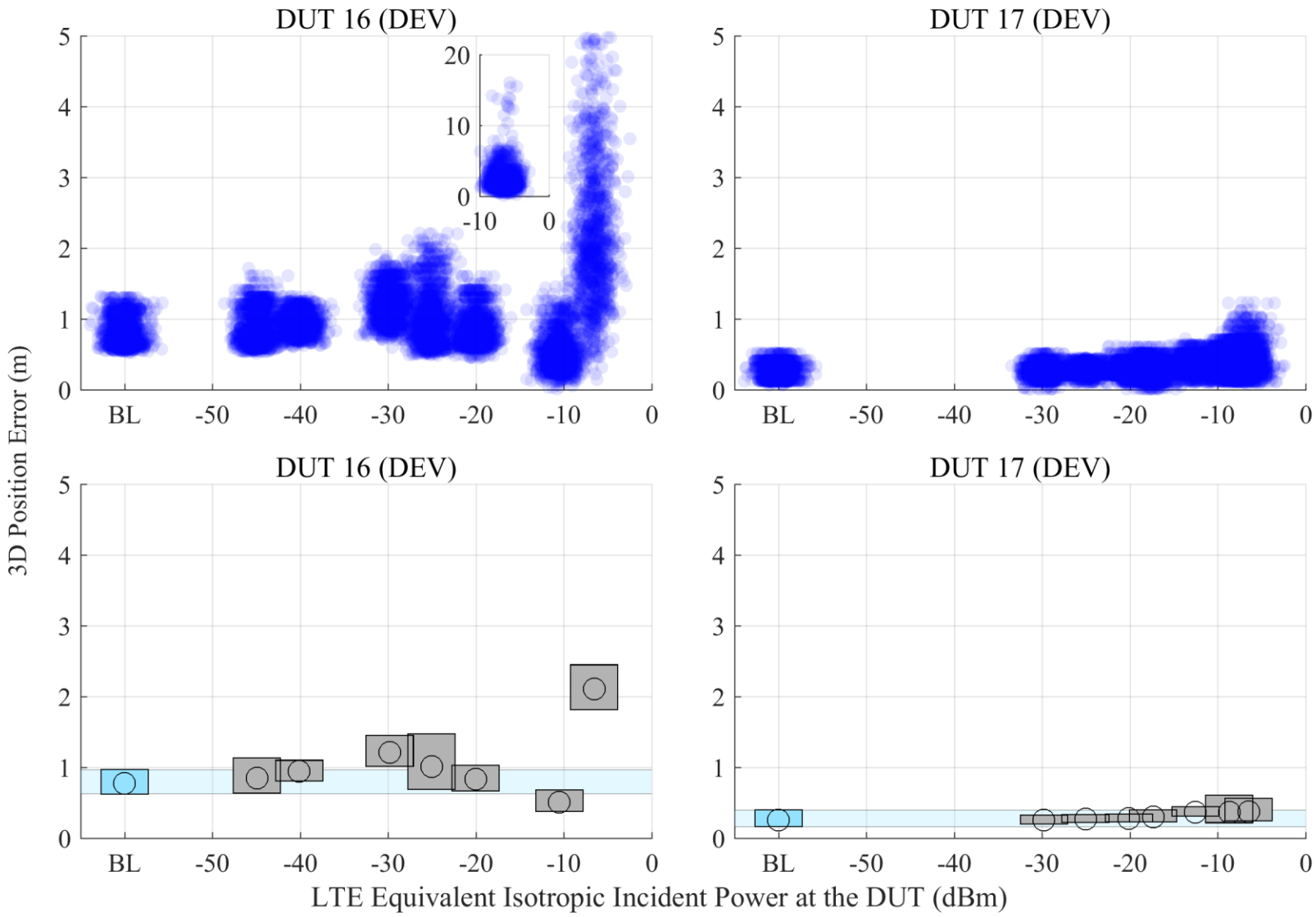
Fig. F.9 – pg. 359

DEV Board

- 3D position error
- Uplink 2
- Nominal satellite condition

Baseline (BL) – No LTE Power



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National Advanced Spectrum and Communications Test Network

Fig. F.10 – pg. 360

DEV Board

- Number of reported satellites in view scatter plot
- Uplink 2
- Nominal satellite condition

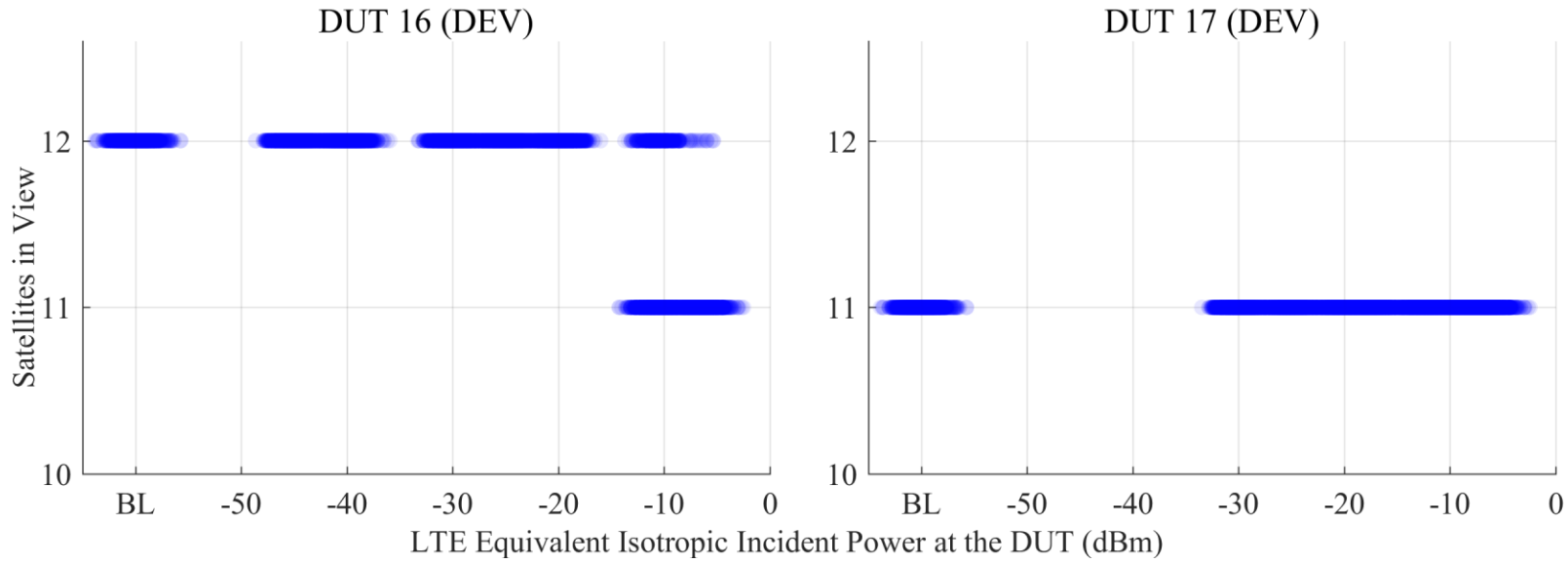

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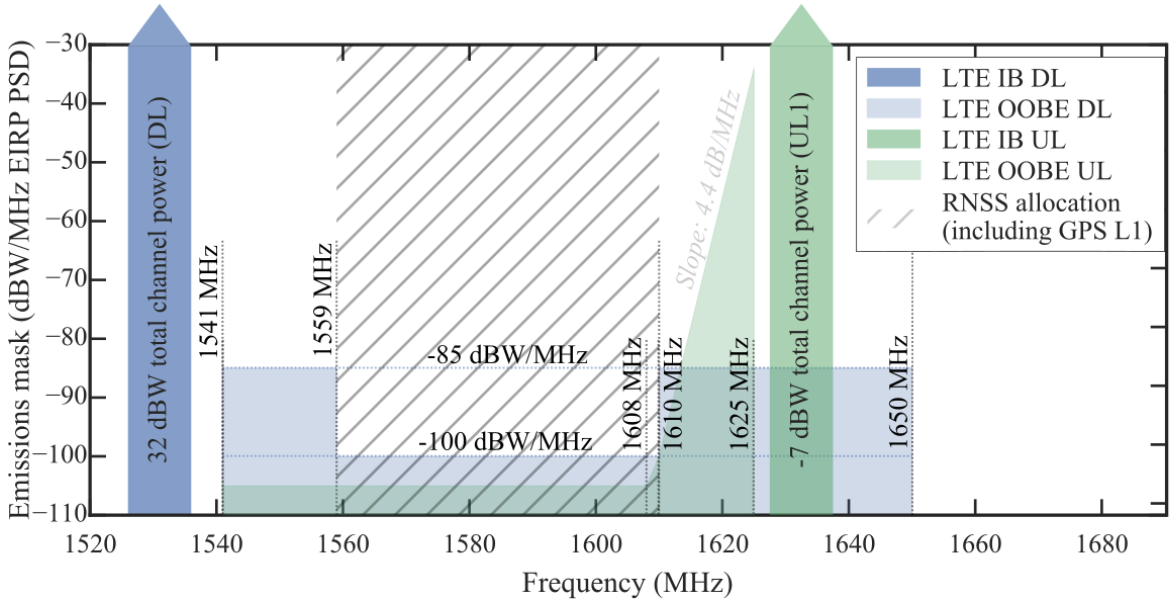
Fig. F.11 – pg. 361

Development Board GPS Receivers

- Nominal Satellite Condition
  - Downlink
  - Uplink 1
  - Uplink 2
  - **Combo DL + UL1**



DEV Board

- C/N0 plots
- Combo DL + UL1
- Nominal satellite condition
- 1200 points per LTE power level per satellite

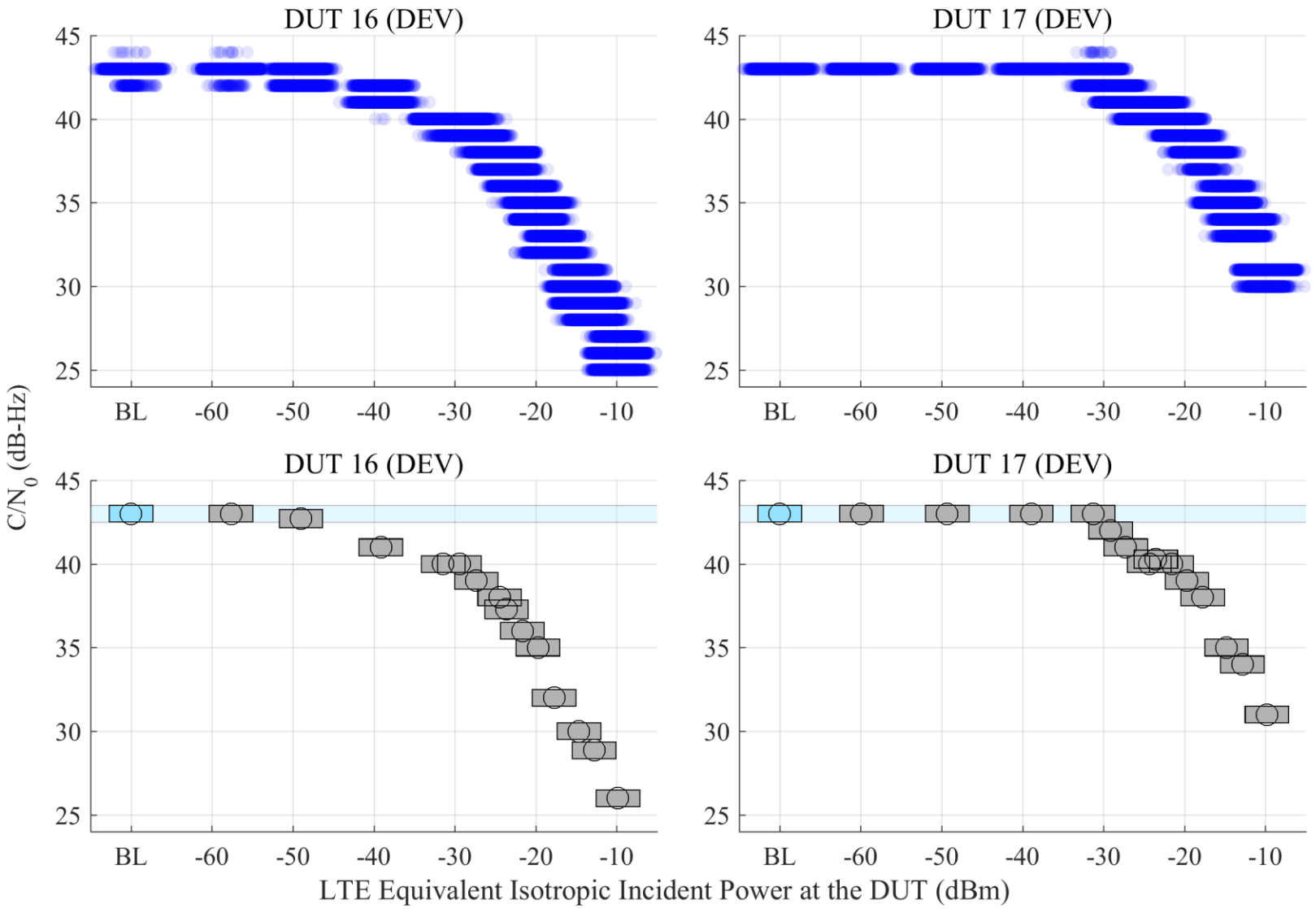


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Fig. F.12 – pg. 362

DEV Board

- 3D position error
- Combo DL + UL1
- Nominal satellite condition

Baseline (BL) – No LTE Power

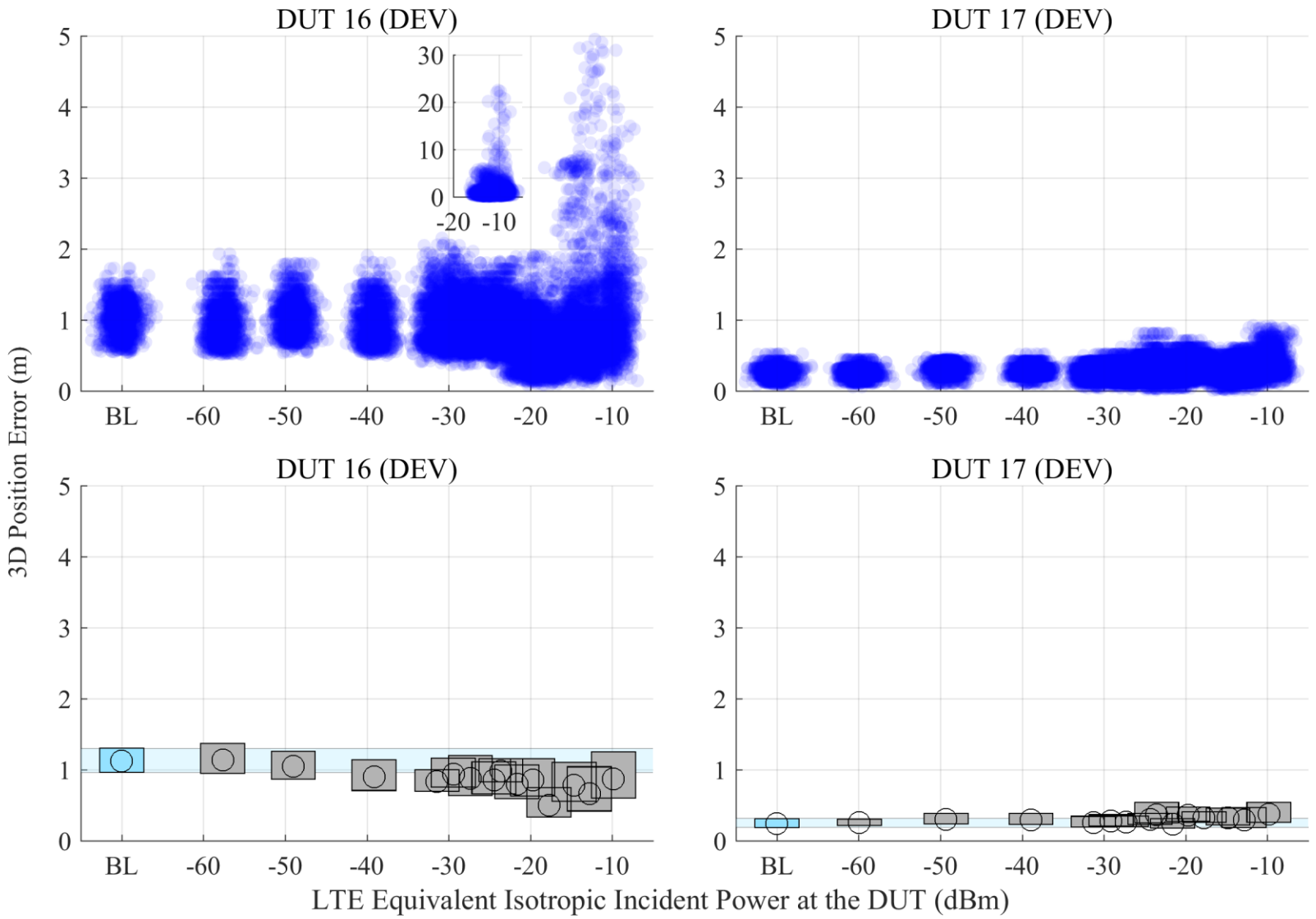

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Fig. F.13 – pg. 363

DEV Board

- Number of reported satellites in view scatter plot
- Combo DL + UL1
- Nominal satellite condition

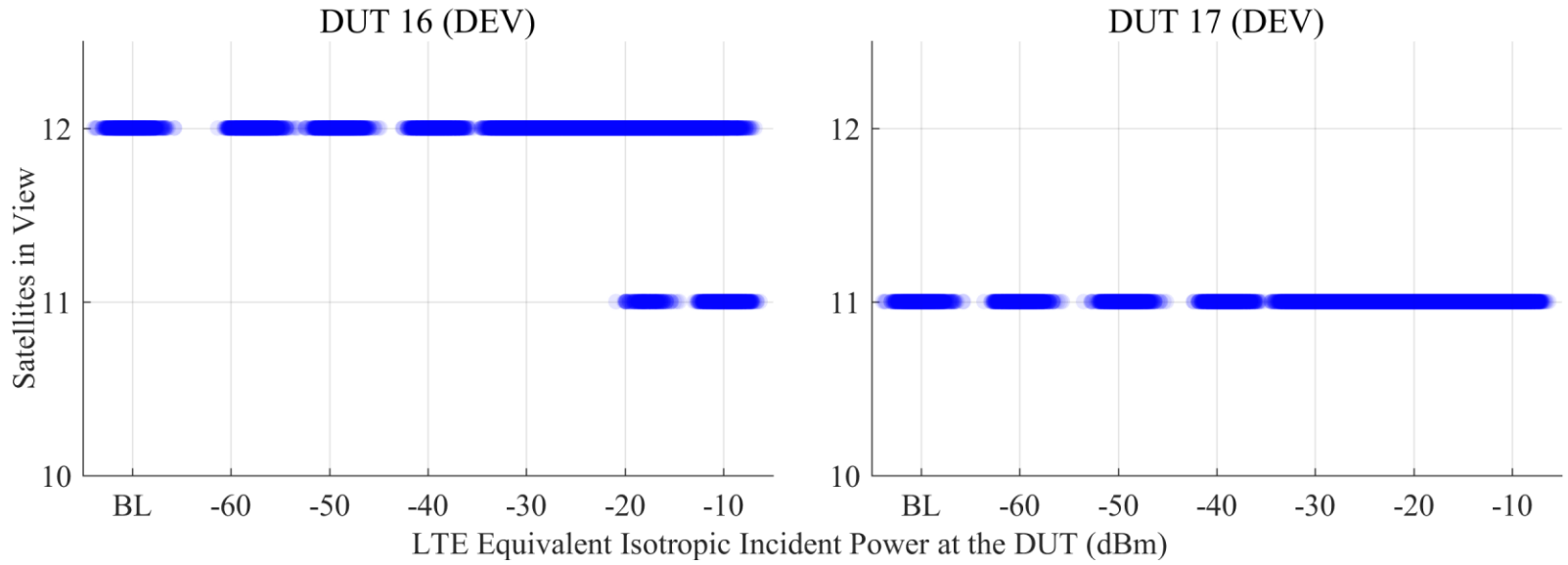

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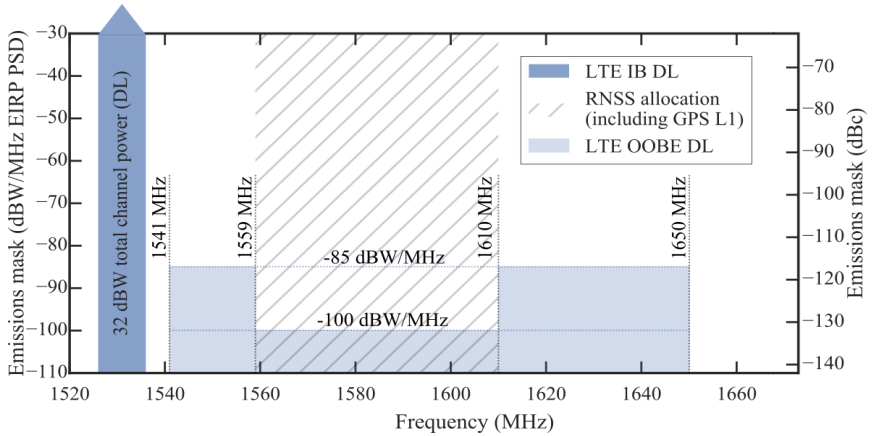
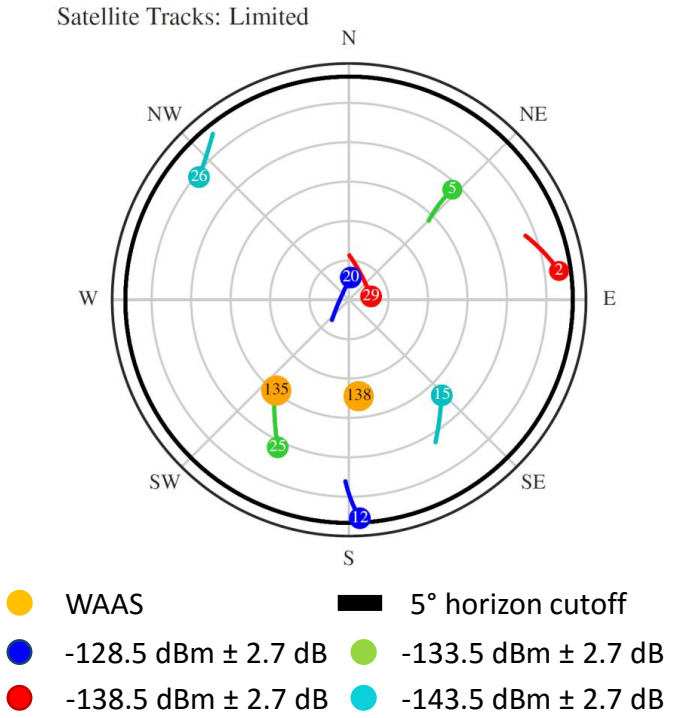
Fig. F.14 – pg. 364

Development Board GPS Receivers

- Limited Satellite Condition
  - **Downlink**
  - Uplink 1





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DEV Board

- C/N0 plots
- Downlink
- Limited satellite condition
- 1200 points per LTE power level per satellite

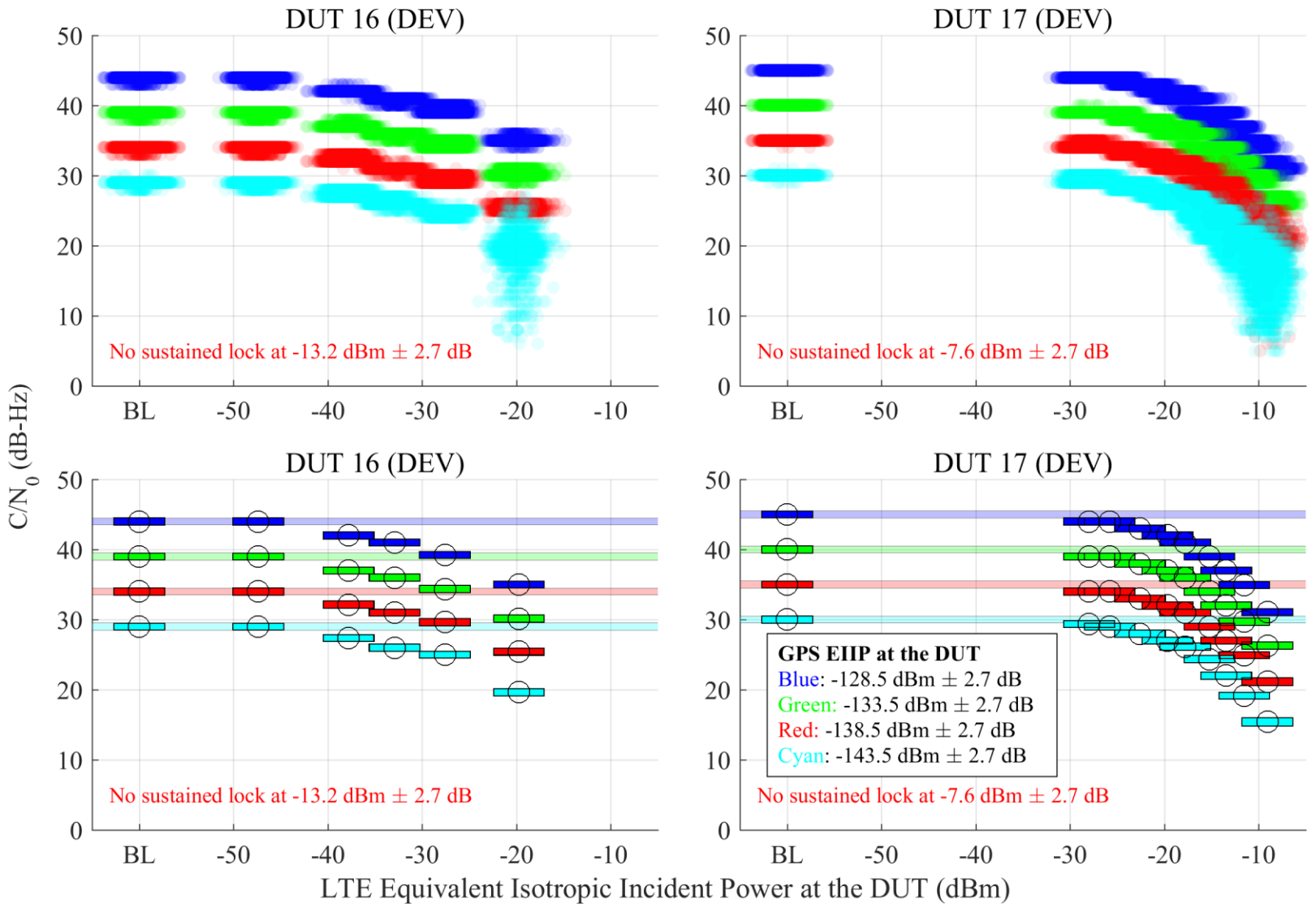

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Fig. F.23 – pg. 376

DEV Board

- 3D position error
- Downlink
- Limited satellite condition

Baseline (BL) – No LTE Power

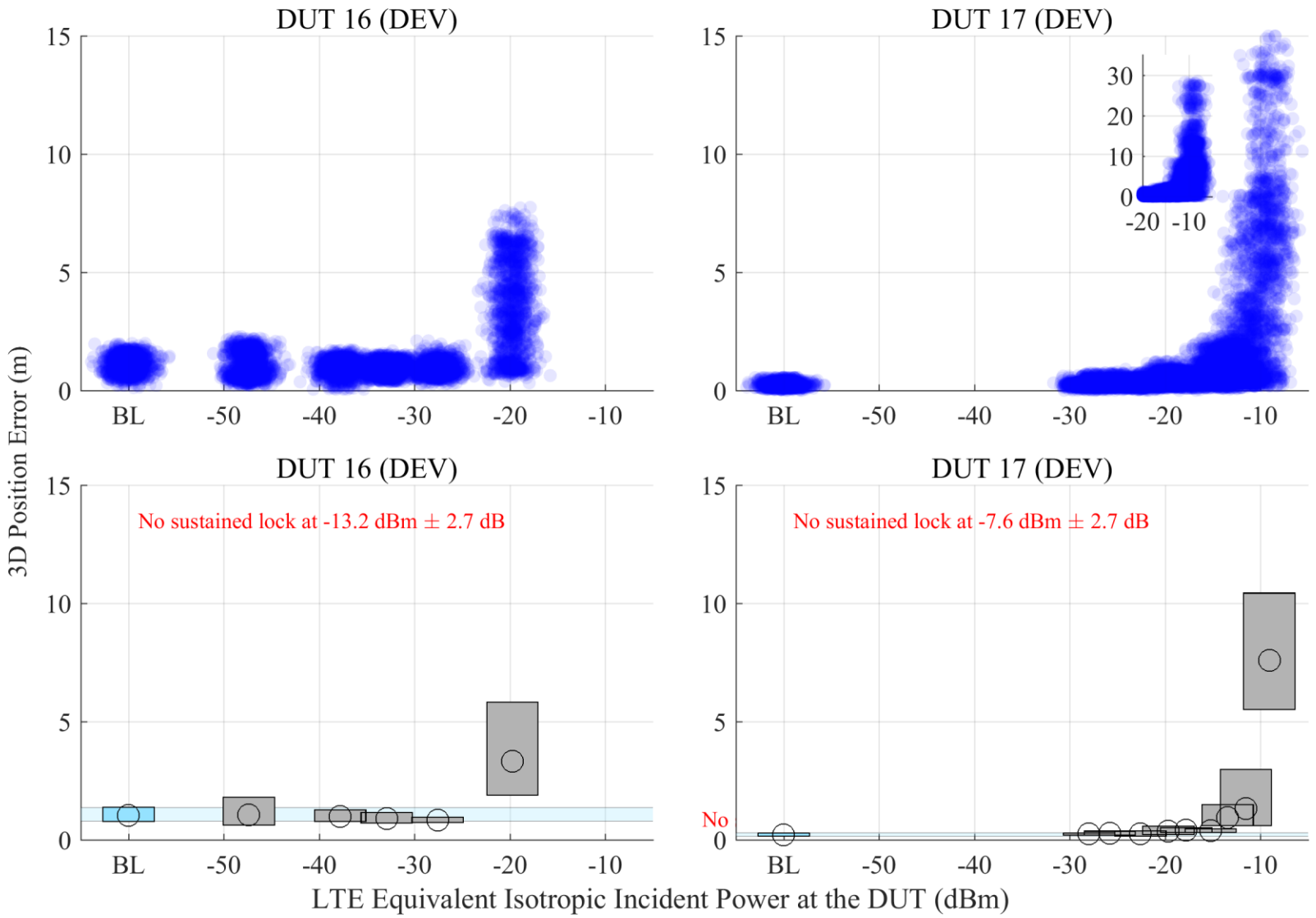

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Fig. F.24 – pg. 377

DEV Board

- Number of reported satellites in view scatter plot
- Downlink
- Limited satellite condition

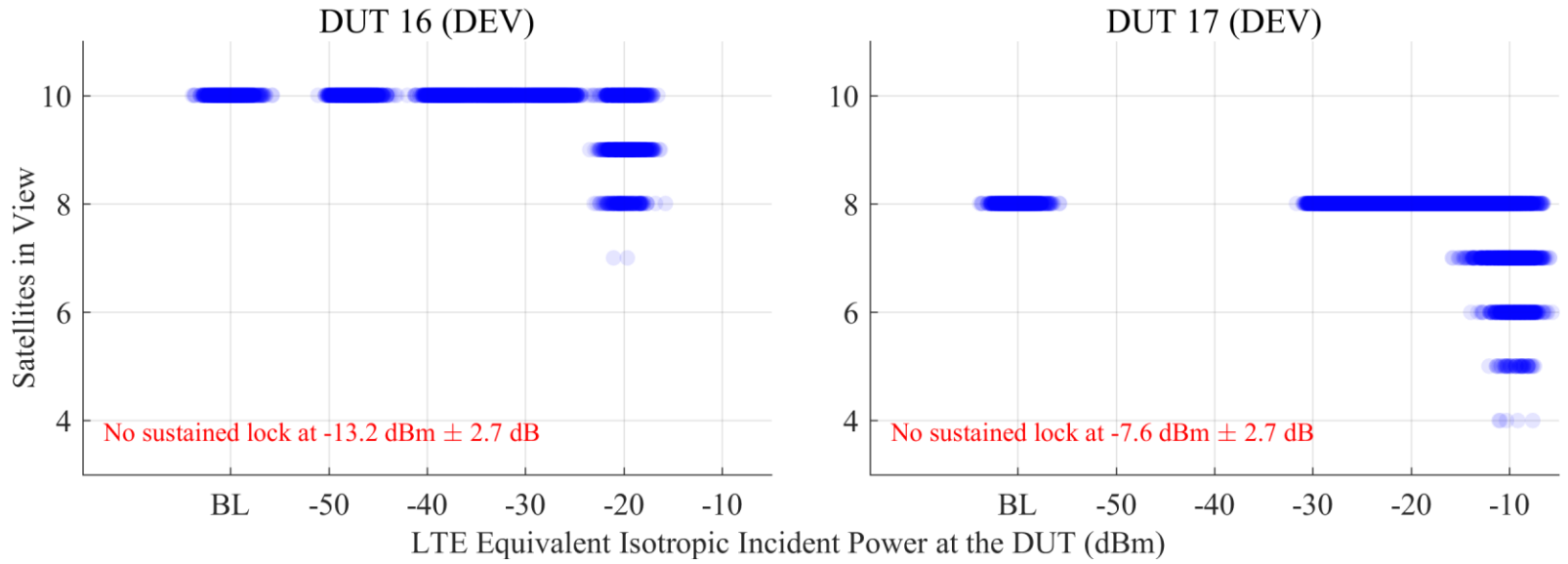

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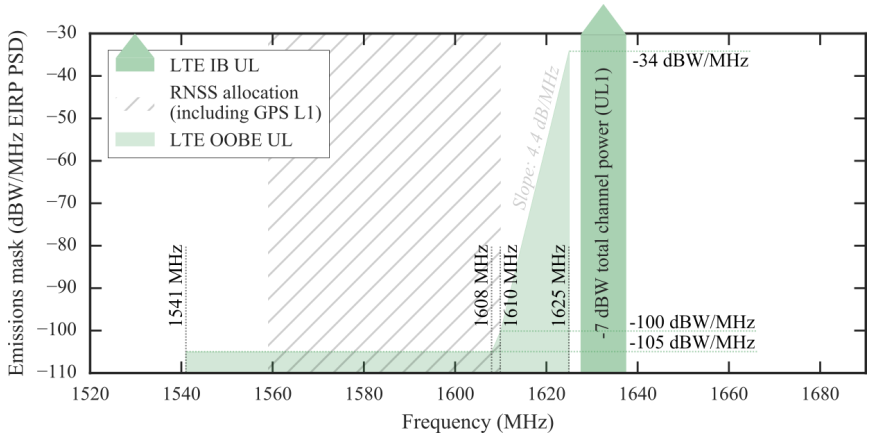
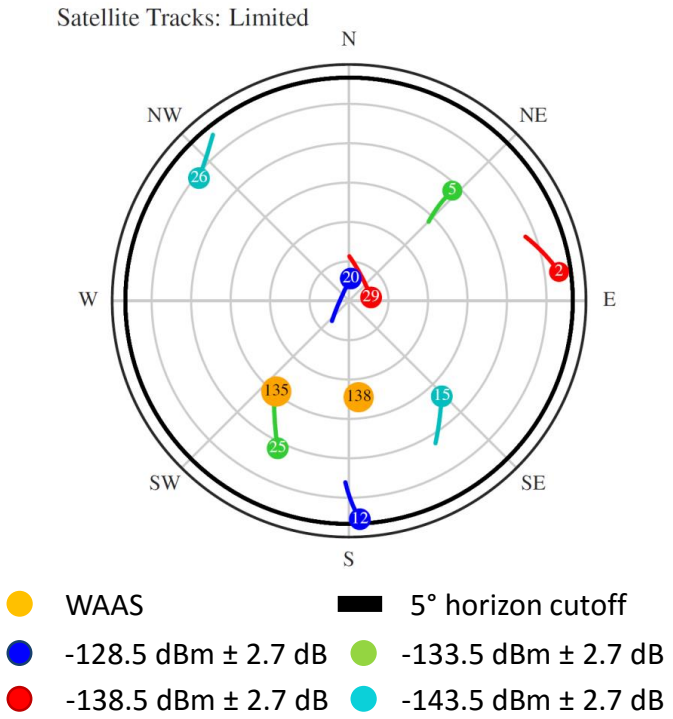
Fig. F.25 – pg. 378

Development Board GPS Receivers

- Limited Satellite Condition
  - Downlink
  - **Uplink 1**





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DEV Board

- C/N0 plots
- Uplink 1
- Limited satellite condition
- 1200 points per LTE power level per satellite

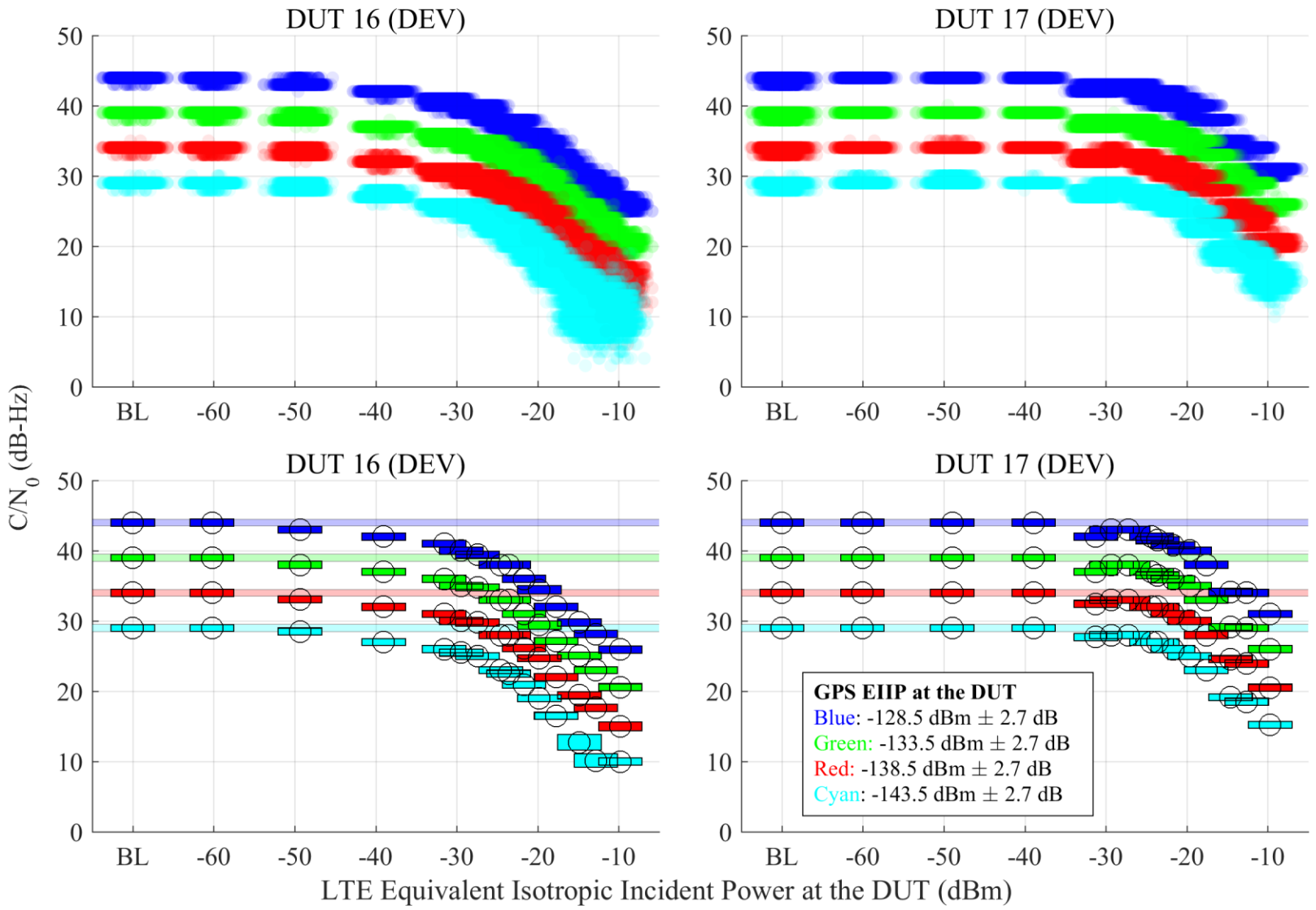

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Fig. F.26 – pg. 379

DEV Board

- 3D position error
- Uplink 1
- Limited satellite condition

Baseline (BL) – No LTE Power

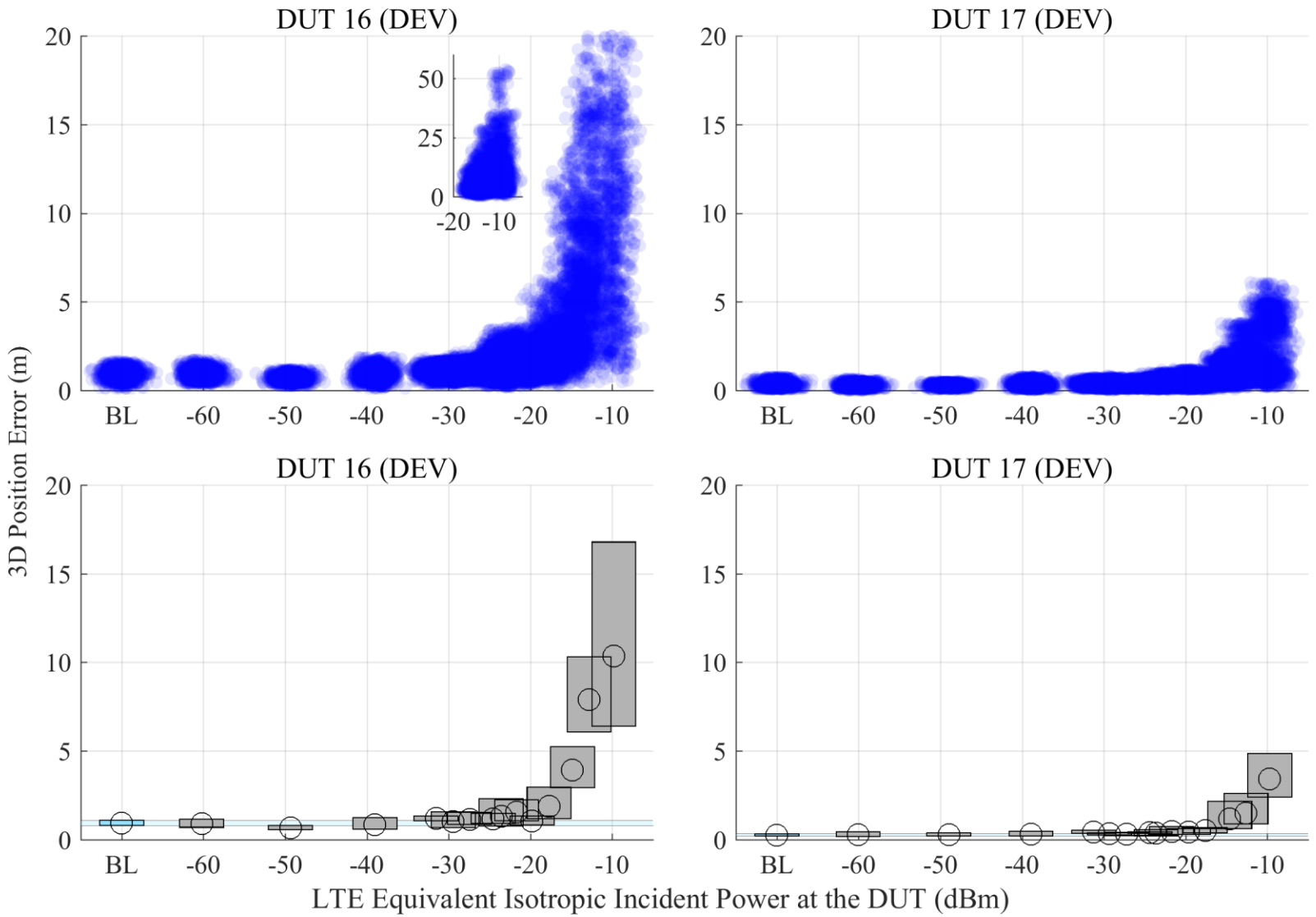

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Fig. F.27 – pg. 380

DEV Board

- Number of reported satellites in view scatter plot
- Uplink 1
- Limited satellite condition

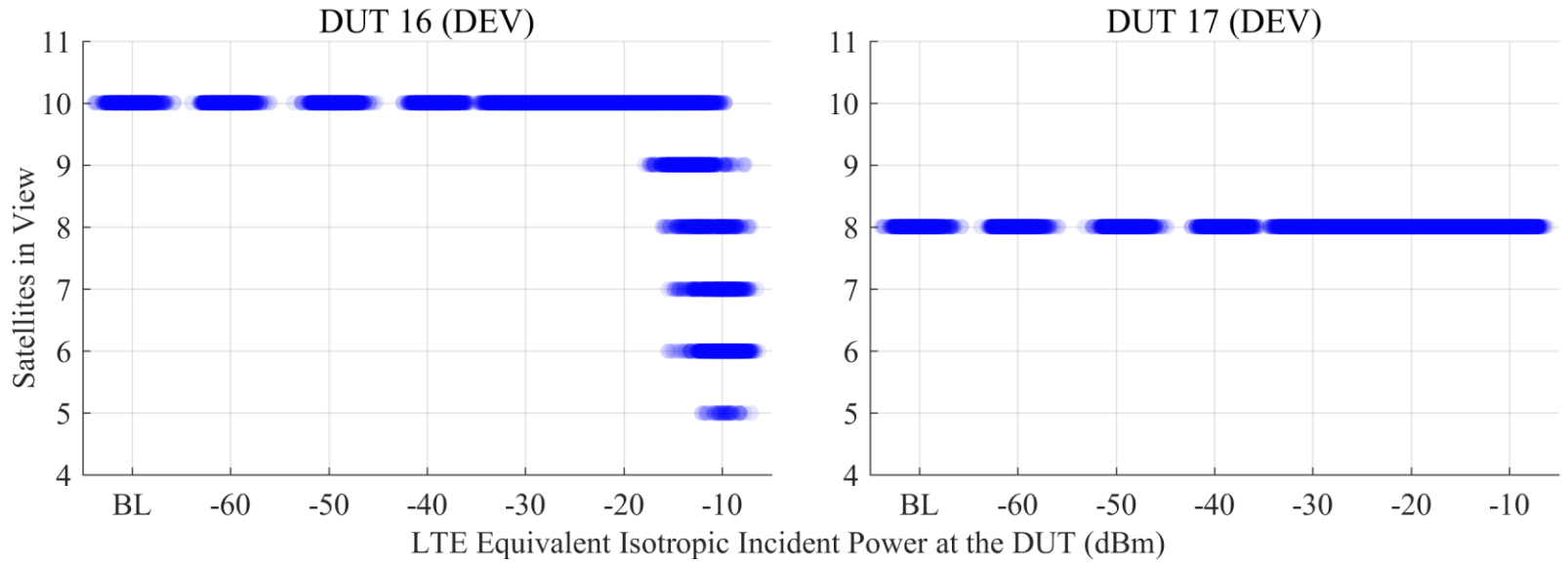
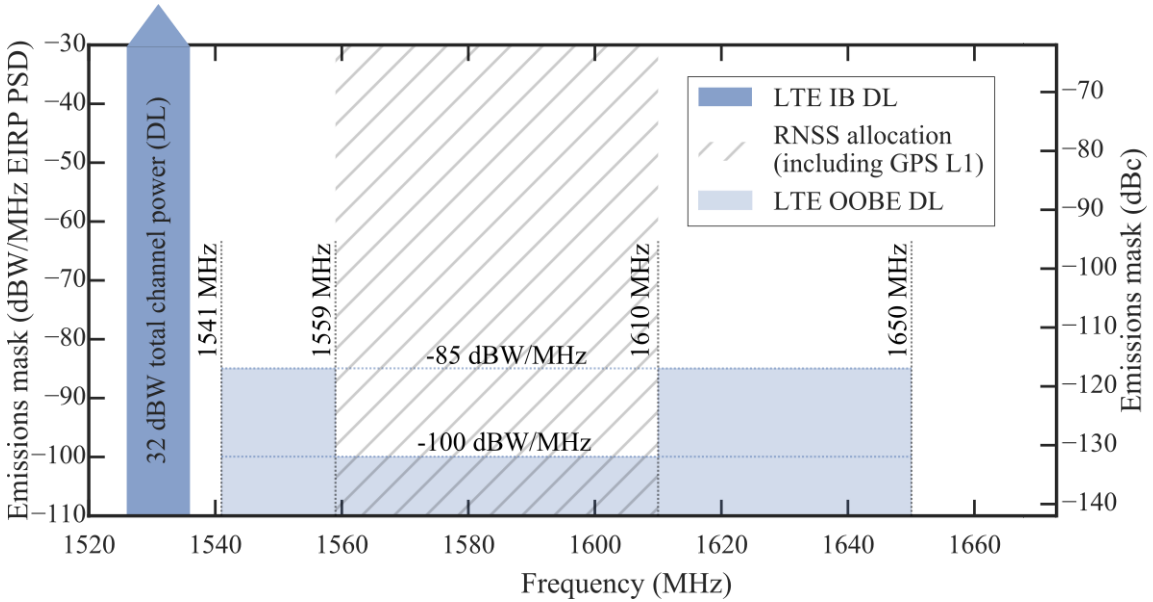


Fig. F.28 – pg. 381

Development Board GPS Receivers

- Nominal Satellite Condition
- TTFF
  - **Downlink**
  - Uplink 1



DEV Board

- TTFF (Cold-Start)
- TTFF scatter plots
- Empirical estimates of the CDF
- Downlink
- Nominal satellite condition
- 100 trials

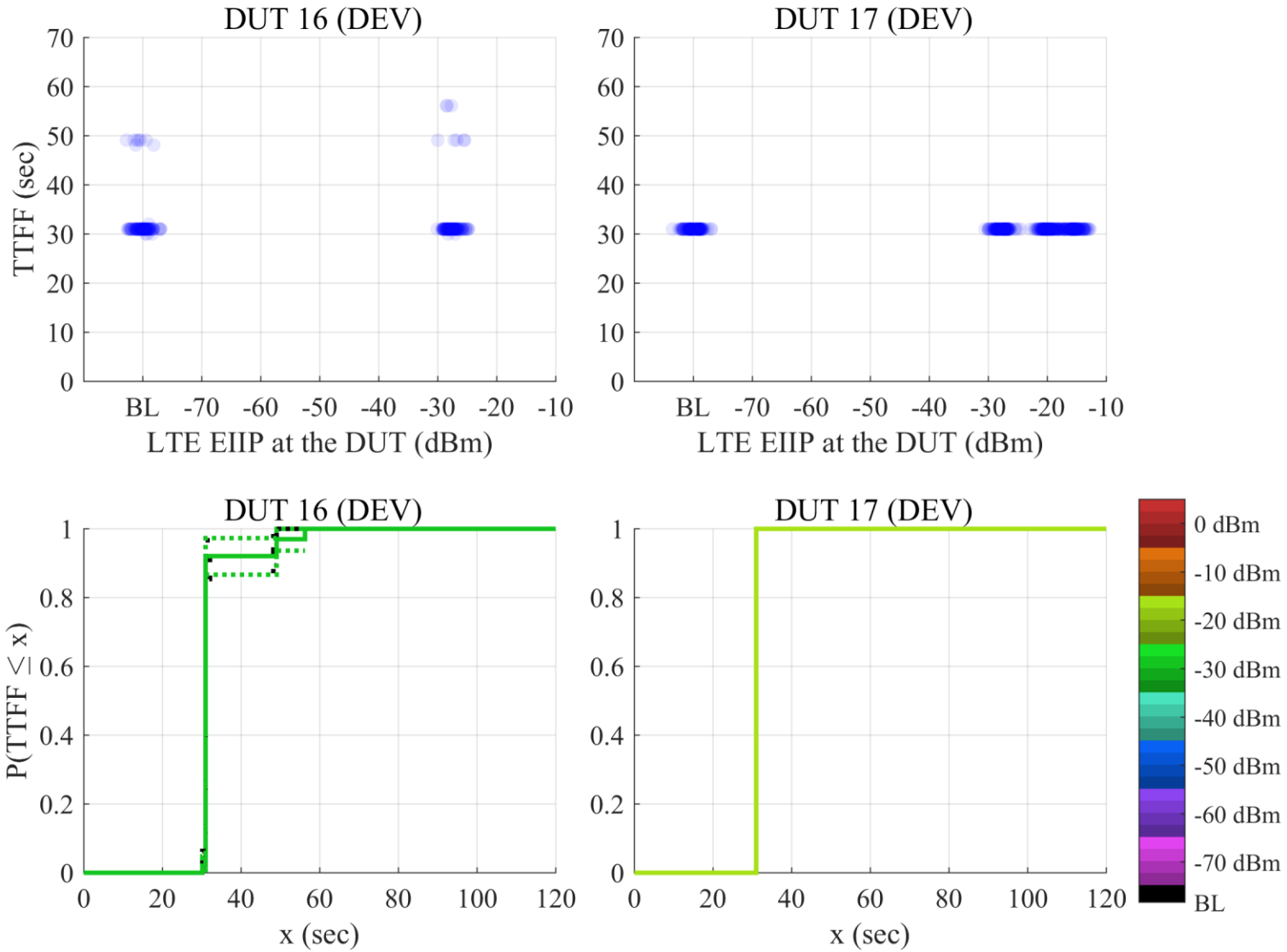
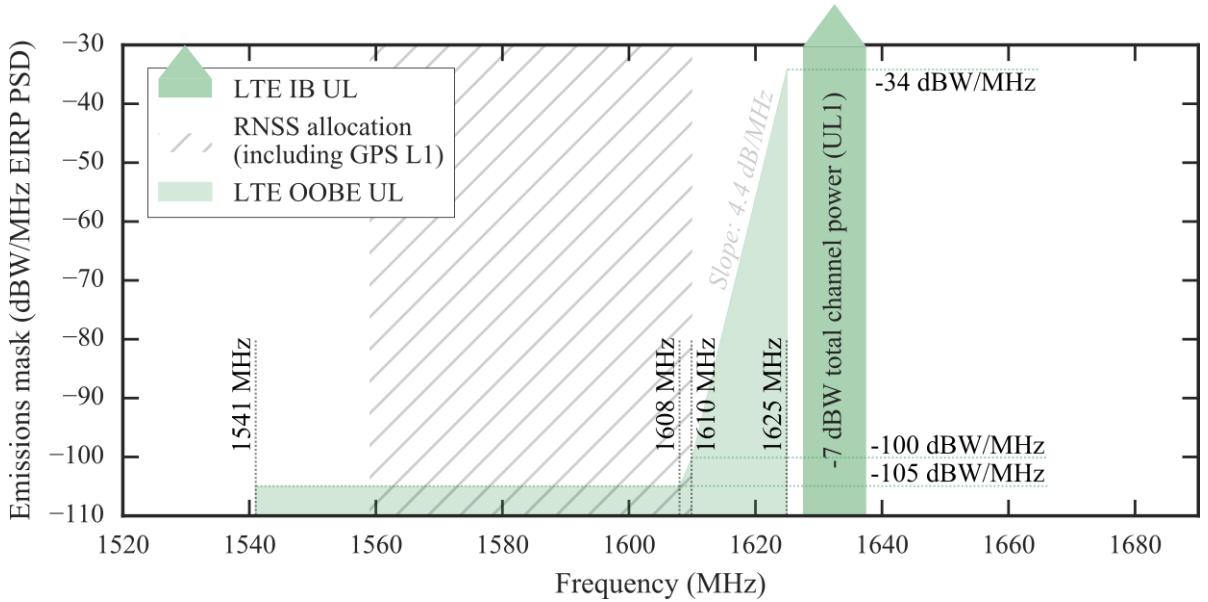


Fig. F.21 – pg. 373

Development Board GPS Receivers

- Nominal Satellite Condition
- TTFF
  - Downlink
  - **Uplink 1**



DEV Board

- TTFF (Cold-Start)
- TTFF scatter plots
- Empirical estimates of the CDF
- Uplink 1
- Nominal satellite condition
- 100 trials

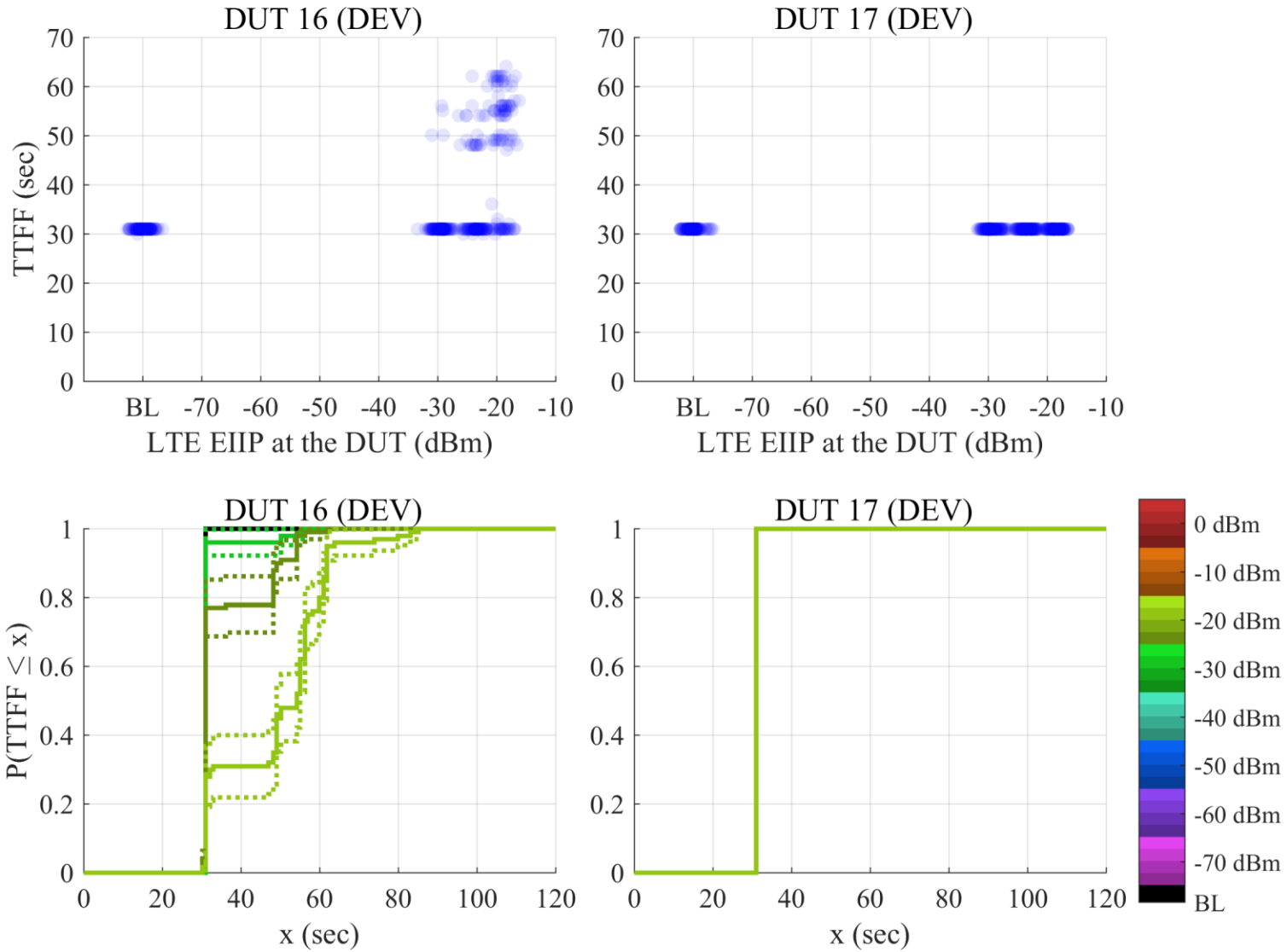


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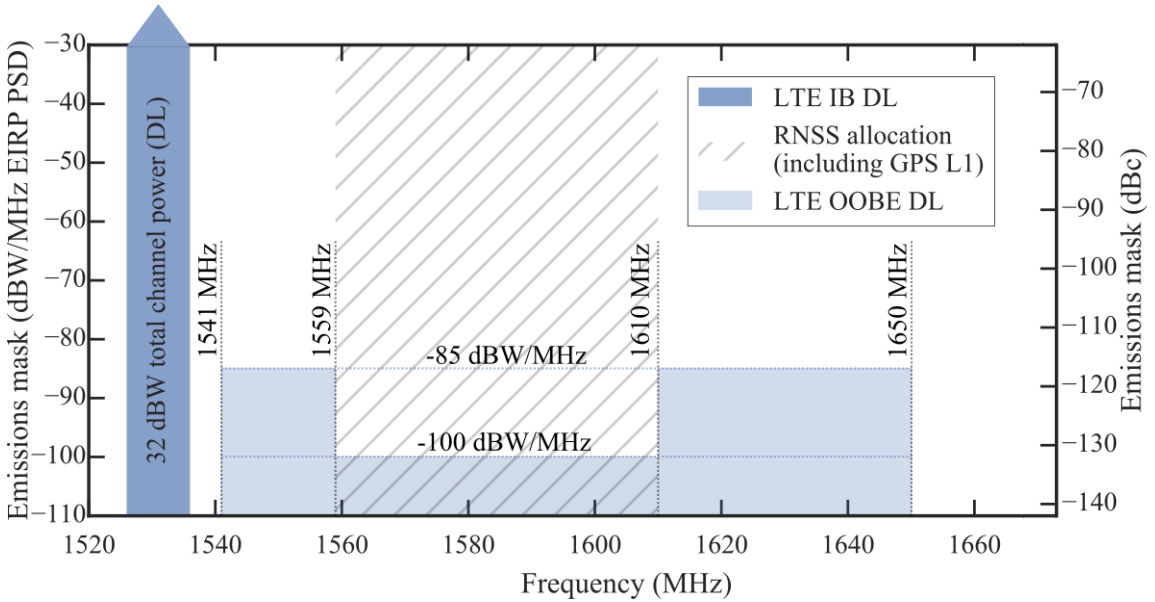
Fig. F.22 – pg. 374

Development Board GPS Receivers

- Nominal Satellite Condition
- Timing
  - **Downlink**
  - Uplink 1
  - Combo DL + UL1



DEV Board

- C/N0 scatter plots (left)
- 95% confidence regions for median C/N_0 (right)
- Number of reported satellites in view scatter plot
- Downlink
- Nominal satellite condition

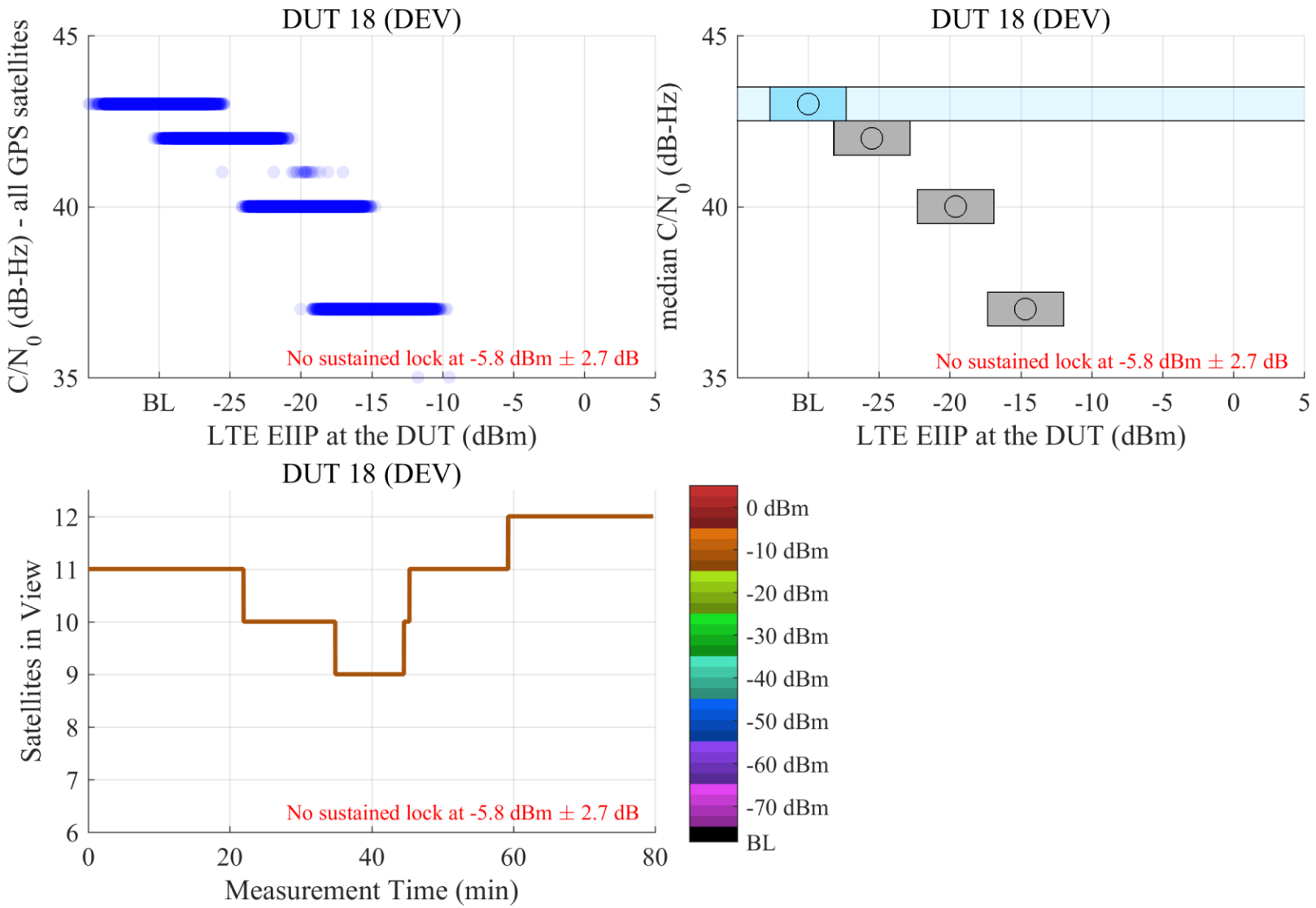


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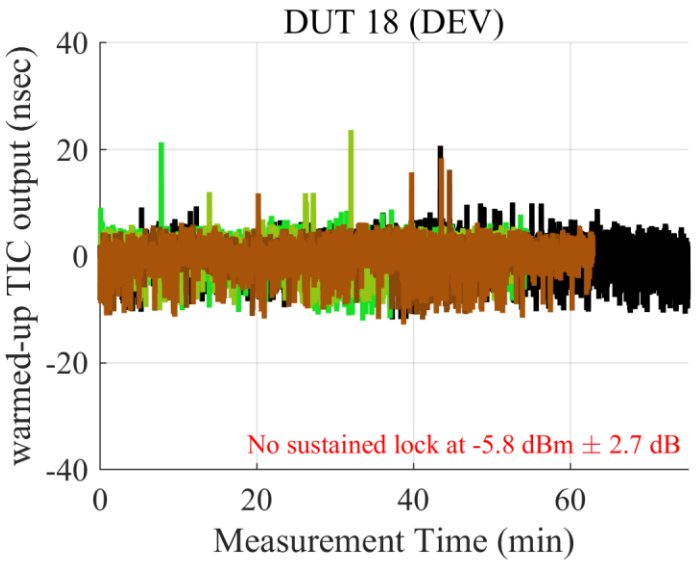
Fig. F.15 – pg. 366

DEV Board

- $\Delta T = PPS_{CSClock}\text{-}PPS_{DUT}$
- TIC data after Warm-up estimation
- Allan Time Deviation Estimate from ΔT after Warm-up time
- Zoomed TDEV
- Downlink
- Nominal satellite condition



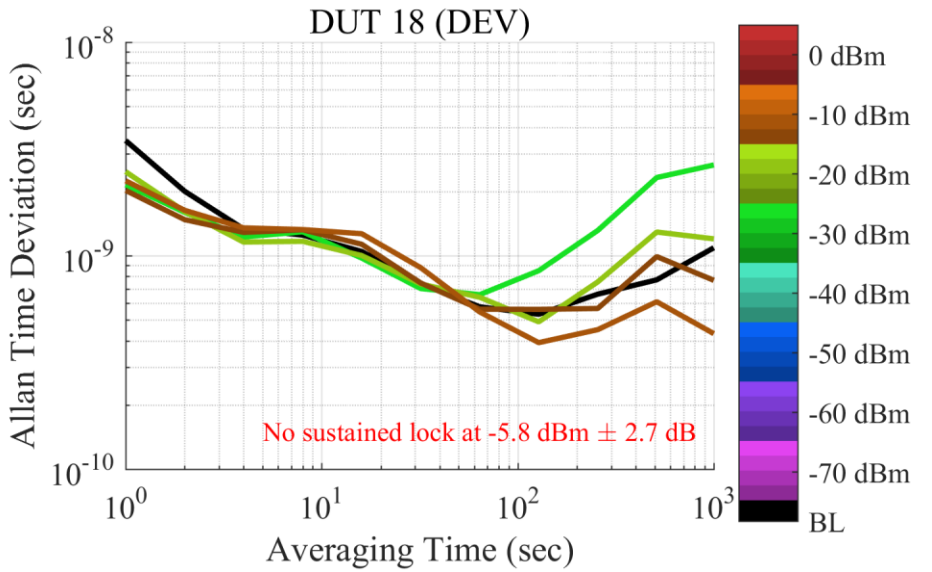


Fig. F.16 – pg. 367

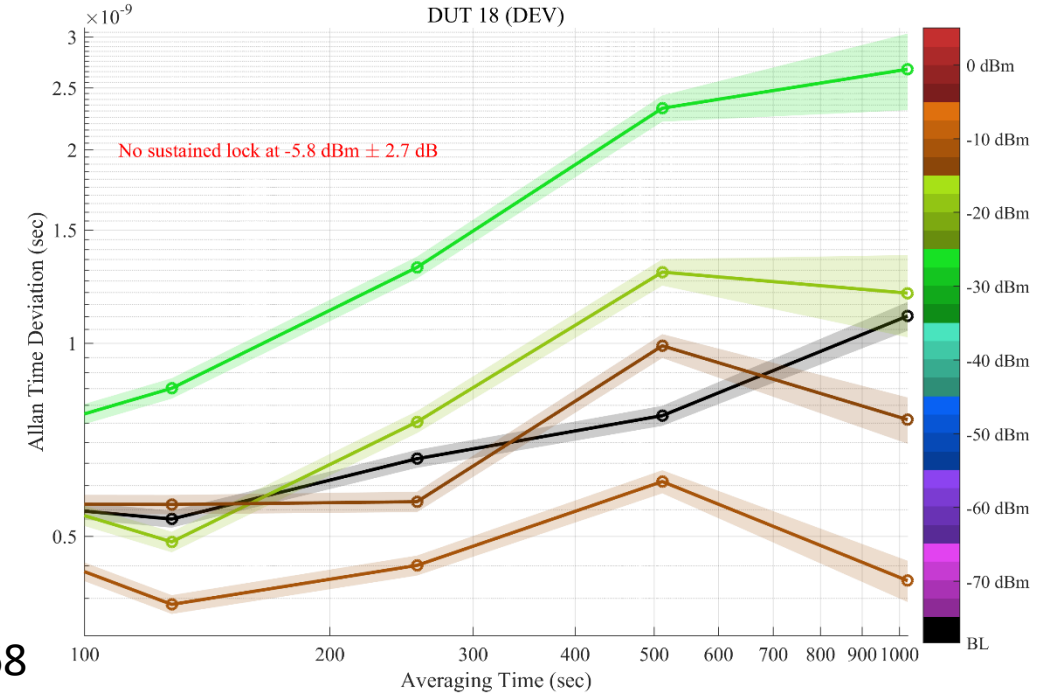


Fig. F.17 – pg. 368

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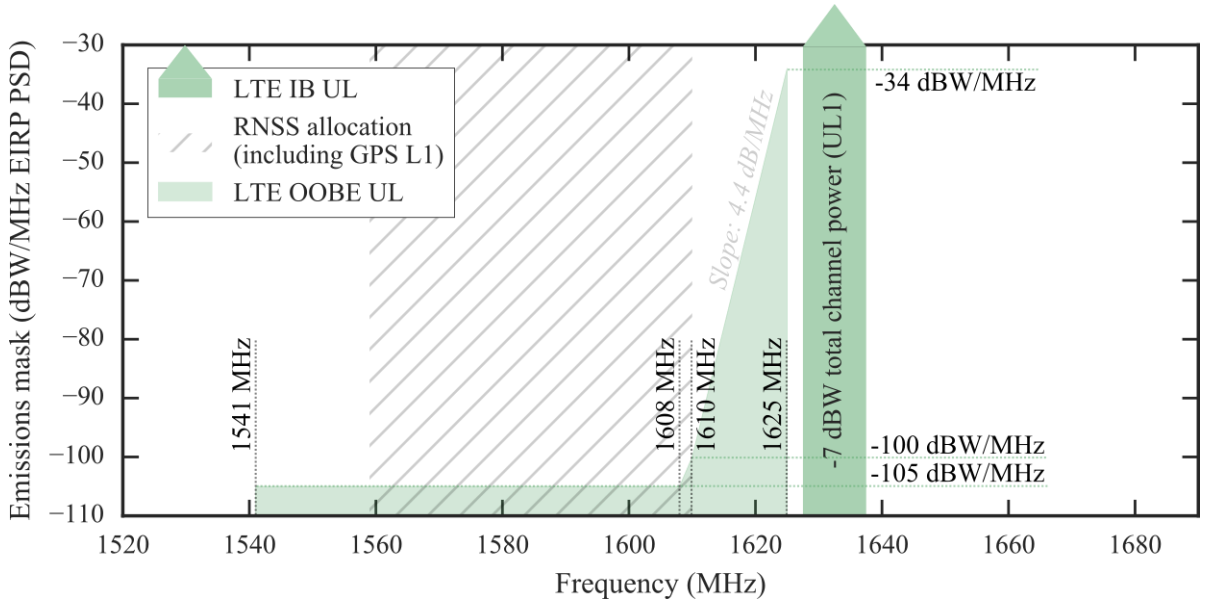
Development Board GPS Receivers

- Nominal Satellite Condition
- Timing
  - Downlink
  - **Uplink 1**
  - Combo DL + UL1



DEV Board

- C/N0 scatter plots (left)
- 95% confidence regions for median C/N_0 (right)
- Number of reported satellites in view scatter plot
- Uplink 1
- Nominal satellite condition

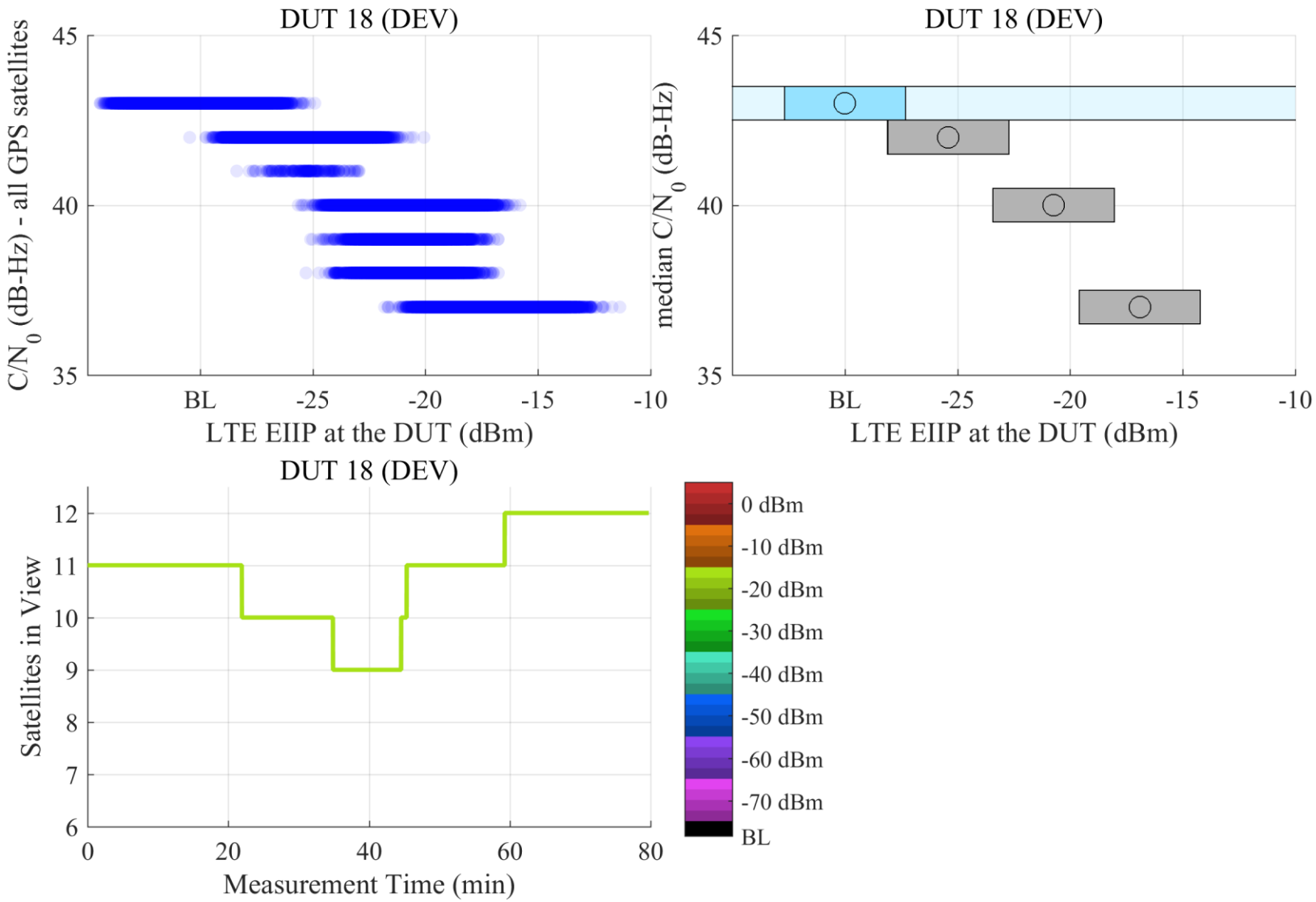


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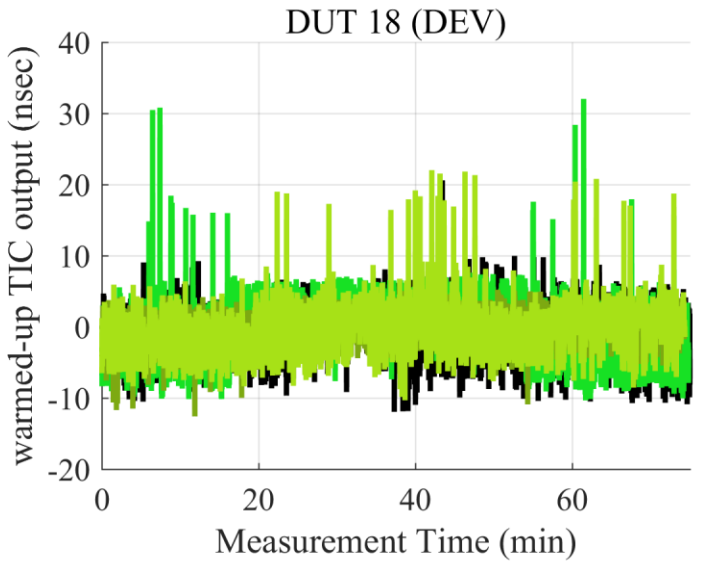
Fig. F.18 – pg. 369

DEV Board

- $\Delta T = PPS_{CSClock}\text{-}PPS_{DUT}$
- TIC data after Warm-up estimation
- Allan Time Deviation Estimate from ΔT after Warm-up time
- Zoomed TDEV
- Uplink 1
- Nominal satellite condition



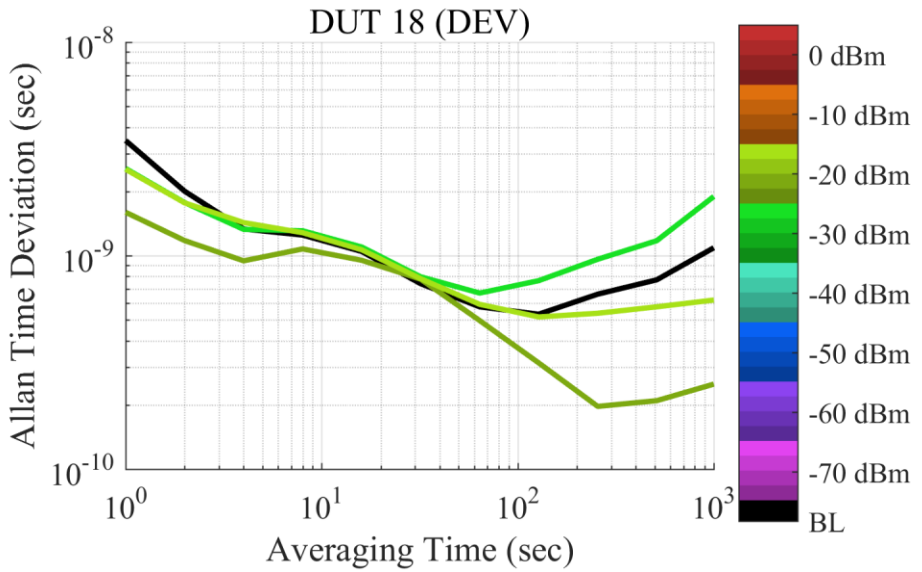


Fig. F.19 – pg. 370

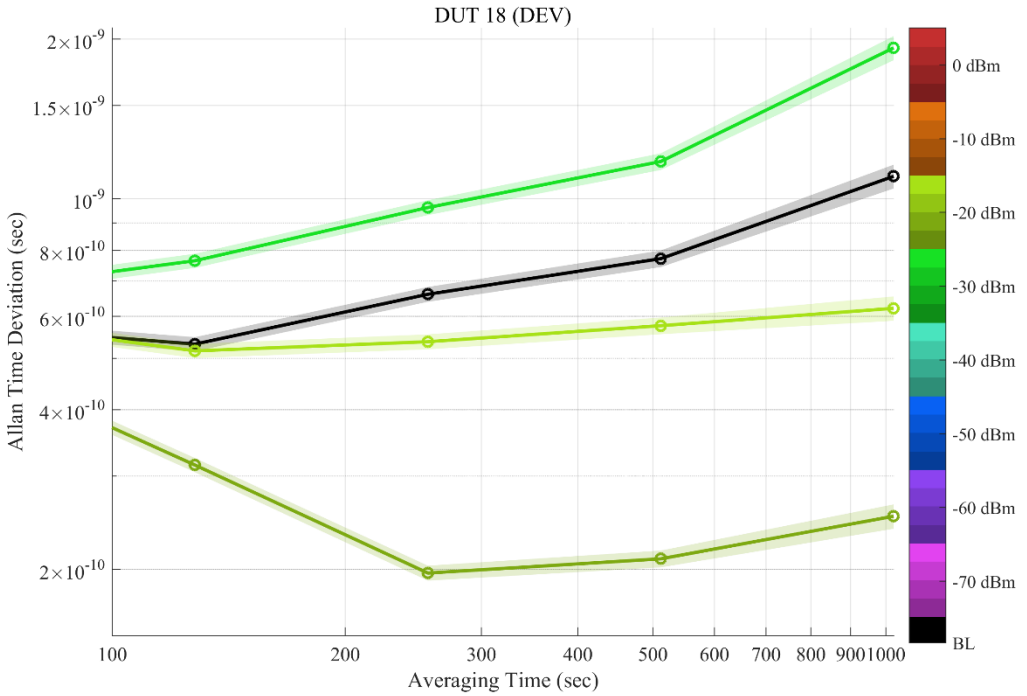


Fig. F.20 – pg. 371

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